Guidelines for Ride Quality Acceptance of Pavements
Final Report

Principal Investigators: Dr. John Collura, P.E.
Dr. Tahar El-Korchi
Research Associates: Kenneth Black
Matthew Chase
Li Jin

Prepared for
The New England Transportation Consortium
April 1997
NETCR 6 Project No. 95-6

Prepared by
University of Massachusetts at Amherst
Department of Civil and Environmental Engineering
Transportation Engineering Program
and
Worcester Polytechnic Institute
Department of Civil and Environmental Engineering

This report was sponsored by the New England Transportation Consortium, a cooperative effort of the Department of Transportation and the Land Grant Universities of the six New England States, and the U.S. Department of Transportation's Federal Highway Administration.

Technical Report Document Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NETCR 6	N/A	N/A

4. Title and Subtitle
Guidelines for Ride Quality Acceptance of Pavements Final Report

5. Report Data
N/A

6. Performing Organization Code
N/A

7. Author(s)
John Collura, Tahar El-Korchi, Kenneth Black, Matthew Chase, Li Jin

8. Performing Organization Report Code
N/A

9. Performing Organization Name and Address

University of Massachusetts
Amherst, MA 01003

10. Work Unite No (TRAIS)
N/A

11. Contract or Grant No.
N/A

12. Sponsoring Agency Name and Address

13. Type of Report and Period Covered
N/A

14. Sponsoring Agency Code
N/A

15. Supplementary Notes The technical monitor on the project was Matthew Turo, Massachusetts Highway Department. Other members of the Project Technical Committee were: Max Grogg, Federal Highway Administration; Keith Lane, Connecticut DOT; Wade McClay, Maine DOT; Mike Ecmecian, Massachusetts Highway Department; Glenn Roberts, New Hampshire DOT; Lee Perkins, Rhode Island DOT and Duane Stevens, Vermont Agency of Transportation.
A Web homepage for this study has been developed and maintained on the Worcester Polytechnic Institute Civil and Environmental Engineering Server. This web site was developed by Prof. T. El-Korchi and Eric Law of the Worcester Polytechnic Institute Civil and Environmental Engineering Department. This site will be maintained as part of the CEE server webpages. The homepage address is: http://cee.wpi.edu/rq/rqas

16. Abstract

An intent of this project is to assist State Highway Agencies (SHAs) in New England in resolving issues and questions associated with the design and use of an initial ride quality specification. To this end, a literature synthesis was conducted to review such issues and questions surrounding the use of current paving practices and the application of different ride quality parameters, measuring devices, and bonus and penalty schedules. In addition, a survey of current ride quality and paving practices of SHAs in New England and in several other states was performed and a field study to examine the ride quality measuring devices being used in New England was also carried out. Finally, a product of this project is a proposed ride quality specification for SHAs in New England. It must be stressed that this proposed specification should be viewed only as a guide.

17. Key Word
Ride Quality, Pavement Roughness, Smoothness International Roughness Index (IRI), Ride Number, Longitudinal Profile

18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
N/A	N/A		N/A

METRIC SYSTEM WITH U.S. EQUIVALENTS

METRIC UNIT	U.S EQUIVALENT (1)
25.4 millimeter (mm)	inch (in)
0.305 meter (m)	foot (ft)
1.609 kilometer (km)	mile (mi)
0.016 meter/kilometer (m/km)	inch/mile (in/mi)
1.609 kilometer/hour (ki/hr)	mile/hour (mi/hr)

TABLE OF CONTENTS

Chapter 1: Introduction....1

1.1 Initial Ride Quality....1

1.2 Description of the Problem....3

1.3 Purpose of Research....4

1.4 Organization of Report....4

Chapter 2: Synthesis of Literature....6

2.1 Ride Quality and Roughness: Concepts and Measurement....6

2.2 Early Development of Roughness Measurement Devices....9

2.3 Current Measurement Methods and Devices....10

2.3.1 Manual Profiling Techniques....12

2.3.2 Direct Profiling Equipment....14

2.3.3 Response-Type Indirect Measurements....20

2.4 Paving Procedures....20

2.5 Selected Ride Quality Studies....................22

2.5.1 Pennsylvania Transportation Institute Study....................22

2.5.2 Arizona Department of Transportation Study....................23

2.5.3 University of Wyoming Study....................27

2.5.4 Colorado Department of Transportation Study....................29

2.6 Major Findings and Conclusions....................31

Chapter 3: A Review of Paving and Ride Quality Practices....................33

3.1 Connecticut Department of Transportation (ConnDOT)....................33

3.2 Maine Department of Transportation (MDOT)....................41

3.3 Massachusetts Highway Department (MHD)....................42

3.4 Massachusetts Turnpike Authority (MTA)....................43

3.5 New Hampshire Department of Transportation (NHDOT)....................44

3.6 Rhode Island Department of Transportation (RIDOT)....................45

3.7 Vermont Agency of Transportation (VAOT)....................46

3.8 Other State Departments of Transportation....................47

3.9 Summary....................50

Chapter 4: A Comparative Study of Ride Quality Measuring Devices 52

4.1 Introduction 52

4.2 Site Selection....................53

4.3 Data Collection and Pavement Profiling Using the Dipstick 53

4.4 Data Collection Procedures 55

4.5 Participating SHAs and Equipment 55

4.6 International Roughness Index (IRI) Statistic 57

4.7 Results 57

4.8 Summary of Findings....................64

Chapter 5: Project Summary and a Proposed Ride Quality Specification....................100

5.1 A Proposed Ride Quality Specification 100

5.1.1 General....................101

5.1.2 Equipment....................101

5.1.3 Indicators of Roughness 102

5.1.4 Payment Adjustment Criteria 102

APPENDICES

1. SHA Survey Questionnaire
2. Contact List of Individuals Involved in the Project
3. RQ Specifications Currently Used in New England and Other Selected States
4. Photographs of Ride Quality Devices
5. Proposed RQ Specification
6. International Roughness Index (IRI) Computation
7. Comparative Summary of State of the Art Equipment
8. Annotated Bibliography
9. References

LIST OF TABLES

2.1 1994 Smoothness Criteria Used for All Roads During the 1994 Paving Season in Colorado 29

2.2 Current Smoothness Criteria Used on Rural Intestates in Colorado (65 mph) 30

2.3 Current Smoothness Criteria Used on Urban Intestates in Colorado (55 mph) 30

2.4 Current Smoothness Criteria Used on Rural Two-lane Roads in Colorado (less than 55 mph) 31

2.5 Current Smoothness Criteria Used on Urban and Thin, Single Lift Roads in Colorado 31

3.1 Summary of Current Paving and Ride Quality Practices in New England 34-36

3.2 Summary of Current Practices for Other Departments of Transportation 37-39

4.1 CT Data North Site 82

4.2 CT Data South Site 83

4.3 MA Data North Site 84

4.4 MA Data South Site 85

4.5 NH Data North Site 86

4.6 NH Data South Site..87

4.7 VT Data North Site..88

4.8 VT Data South Site.. 89

4.9 Dipstick Data North and South Sites 90

4.10 Summary of Results (Metric Units)...91

4.11 Summary of Results (English Units).. 92

4.12 Effect of Accuracy (Device IRI-Dipstick IRI) 93

4.13 Comparison between Different Devices

(Combined Speed, North)..94

4.14 Comparison between Different Devices

(Combined Speed, South) 95

4.15 Speed Effect........... 96

4.16 Effect of Different Sensors 97

4.17 Summary of Data- Effect of Repeatability 98

4.18 Effect of Accuracy..99

LIST OF FIGURES

2.1 The IRI Scale....8

2.2 Blanking Band Applied to Profilograph Trace....19

4.1 The Location of Selected Sites....54

4.2 Station Marking Operation and Dipsticking....56

4.3a The IRI Value (North 30 mph)....58

4.3b The IRI Value (North 40 mph)....59

4.3c The IRI Value (South 30 mph)....60

4.3d The IRI Value (South 40 mph)....61

4.4a The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 North 30 mph) IRI....65

4.4b The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 North 40 mph) IRI....66

4.4c The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 South 30 mph) IRI....67

4.4d The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 South 40 mph) IRI....68

4.4e The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 North 30 mph) IRI....69

4.4f The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 North 40 mph) IRI 70

4.4g The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 South 30 mph) IRI 71

4.4h The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 South 40 mph) IRI 72

4.4i The Regression Analysis between Dipstick IRI and SHA Device (MA North 40 mph) IRI 73

4.4j The Regression Analysis between Dipstick IRI and SHA Device (MA South 40 mph) IRI 74

4.4k The Regression Analysis between Dipstick IRI and SHA Device (NH North 30 mph) IRI 75

4.4l The Regression Analysis between Dipstick IRI and SHA Device (NH North 40 mph) IRI 76

4.4m The Regression Analysis between Dipstick IRI and SHA Device (NH South 30 mph) IRI 77

4.4n The Regression Analysis between Dipstick IRI and SHA Device (NH South 40 mph) IRI 78

4.4o The Regression Analysis between Dipstick IRI and SHA Device (VT North and South 40 mph) IRI 79

CHAPTER 1

INTRODUCTION

1.1 Initial Ride Quality

Initial ride quality is an important characteristic in determining the acceptance of a newly paved road. The user can easily recognize such imperfections as bumps and dips and may experience an uncomfortable ride. Smooth riding pavements provide a safe and comfortable ride for users of a roadway.

Some experts in highway construction contend that smoother pavements not only benefit users but actually perform better than excessively rough pavements. It is therefore important to understand and to measure road roughness in a consistent way. Road roughness can be conceptualized as the deviation of a pavement surface from a true planar surface, with characteristic dimensions that affect ride quality (1).

The majority of state highway agencies (SHAs) in New England measure roughness in units specified by the International Roughness Index (IRI). This standard unit of measurement was developed in 1982 by the World Bank in Brazil under the International Road Roughness Experiment (IRRE) (2). The IRI is based on an analysis of longitudinal profile and is expressed in units of inches per mile or meters per kilometer. When a pavement lacks roughness, it is referred to as a smooth pavement.

A contractor is typically responsible for paving a smooth riding road that will be acceptable to the user and the responsible highway agency. Many highway agencies are currently establishing ride quality specifications that require the contractor to meet a certain level of smoothness (i.e., an IRI value) after initial construction. These agencies may also incorporate incentives and disincentives into their payment formulas to encourage contractors to meet their requirements. This payment formula in part dictates how much the contractor is paid for the paving job.

Contractors in New England at present use a straightedge as their main device for testing pavement smoothness. The straightedge, which can be used while paving is still in progress, is the most economical device for the contractor. The straightedge is placed on the surface of the pavement, and the distance between the bottom of the device and the surface of the pavement is measured. The pavement is deemed acceptable if the measured distance is less than a specified tolerance limit.

Most SHAs in the United States use more sophisticated equipment to measure smoothness. Some use laser, optical, infrared, or acoustic sensors to measure the profile of a newly paved road. Others use response-type equipment that records vertical displacement. It has been determined that the profilograph, a response-type system, is the most widely used device in the United States for assessing the initial ride quality of pavement (3).

Approximately 18 SHAs in the United States are implementing initial smoothness specifications that include incentives and disincentives in their payment schemes (3). These specifications, which have been designed and implemented with the notion that lower initial pavement roughness will result in a better performing pavement, provide clear guidelines for contractors to use in producing a smooth pavement.

1.2 Description of the Problem

Because state highway officials in New England are in the process of designing and implementing initial ride quality specifications, they are highly interested in addressing a number of issues and questions relating to ride quality acceptance (4). Such questions include:

- What is a smooth riding pavement and how can smoothness be measured quantitatively?
- How can we distinguish between different levels of smoothness (or ride quality)?
- What is an appropriate level of ride quality for various functional classes of highways?
- Do acceptable (or tolerable) levels vary by pavement type or method of construction?
- Does an initial ride quality specification enhance the overall quality and life of a pavement?
- Does the use of such specifications lead to increased construction costs or lengthened schedules?
- What are advantages, disadvantages, and limitations of various pieces of equipment and measurement methods, and are these devices and methods equally appropriate for rigid and flexible pavements?
- How might payments to contractors be associated with smoothness specifications?

The consensus among SHA officials in New England is that obtaining answers to these questions will provide a basis for proper consideration and development of appropriate ride quality acceptance specifications and suitable measurement procedures and methods for their states (4). One key purpose of this report is to focus on these questions to further the development of initial ride quality specifications.

1.3 Purpose of Research

The primary purpose of the research summarized in this report is to develop guidelines to assist New England SHAs in the formulation of appropriate specifications and implementation procedures for ride quality on new pavements. Implicit in the pursuit of this purpose is the understanding that no one specification and procedure will meet all the needs of all six SHAs. Specifications and procedures are likely to vary depending on each SHAs intended objectives, paving practices (e.g., AC, PCC), availability of measurement equipment and other factors (4). A special effort has been made to offer guidelines that are suitable for use in New England and sensitive to the region's environmental and geographic conditions; the administrative, construction, and paving practices of each state; the availability of staff, equipment, and other resources in each state; legal issues and their implications; and other factors.

1.4 Organization of Report

Initial ride quality is an important issue for all state highway agencies. This report presents guidelines for the preparation of a ride quality specification that is suitable for each individual state. To provide a broader context for its findings and recommendations, the report summarizes current paving practices in New England and reviews ride quality specifications now in use by other state highway agencies in the United States.

Chapter 2 of this report reviews past and ongoing practices and research related to pavement ride quality in the United States and other countries. This literature review (per Task 1 of this study) is intended to enhance understanding of the concept of ride quality and to broaden the base of information available to the reader about techniques and devices used to measure ride quality. The major findings and conclusions of the literature review are summarized to help SHA personnel in New England address the questions of concern outlined above.

Chapter 3 describes the results of a survey conducted among the state highway agencies in New England to identify the paving and initial ride quality practices currently in use or under development in each state (per Tasks 2, 3, and 4). A special effort was made to understand how much progress the states had made in the implementation of a ride quality specification. The ride quality practices and techniques of selected state highway agencies outside New England are also reviewed and discussed.

In Chapter 4, ride quality parameters and measurement devices and techniques are defined and compared (per Task 5).

In Chapter 5 guidelines for ride quality acceptance specifications are proposed (per Tasks 6 and 7).

CHAPTER 2

SYNTHESIS OF LITERATURE

The purpose of this chapter is to review and synthesize literature related to current paving practices, roughness measurement, and other ride quality issues. Documents were obtained from over 10 agencies, including the Federal Highway Administration (FHWA). A particular effort was made to identify literature on ride quality, roughness concepts, and measurement methods and equipment now being used to assess ride quality. The Transportation Research Information Service (TRIS), a computerized literature database, was also used to help identify appropriate literature. Furthermore, the annotated bibliography in the NCHRP Project 1-31Technical Memorandum (3) was reviewed with special attention. Information from this bibliography was used to formulate a questionnaire that shaped and guided meetings with all SHAs in New England.

2.1 Ride Quality and Roughness: Concepts and Measurement

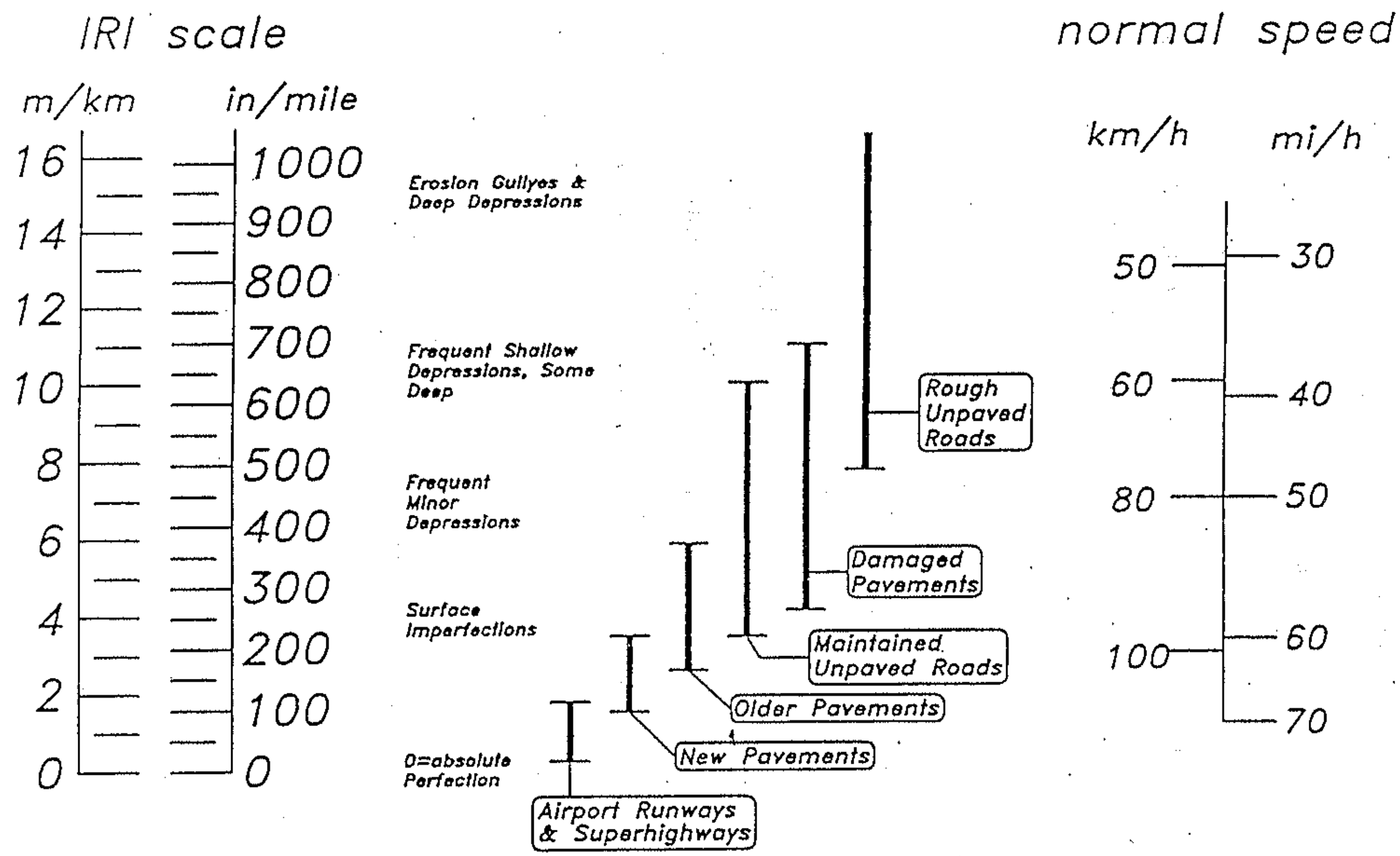
Ride quality is a phenomenon resulting from the interaction of a vehicle and a road surface profile. Experienced by the vehicle, its occupants, and its cargo, ride quality is a function of both road surface profile, or roughness, and certain vehicle parameters, such as the dynamic characteristics of suspension, tires, body mounts, and seats. Pavement smoothness and roughness are at opposite ends of the same scale (6).

Smoothness of a pavement is a good indicator of ride quality, but other factors are also important.

In the 1950s, the American Association of State Highway Officials first attempted to correlate the findings of a ride quality rating panel to measured profile information (3). Subsequently, the Pavement Serviceability Rating index (PSR) was created. The PSR assigns a value of 5 to perfect pavements and a value of 0 to pavements sufficiently rough to damage the vehicle (7).

Yoder & Milhous found that a group of 15 or more trained evaluators was sufficient to provide a stable rating system (8), while Gulen et. al. found that it was possible for 10 or fewer randomly chosen raters to provide sufficiently consistent, repeatable roughness evaluations (9). The Pavement Serviceability Index (PSI) was developed to estimate the PSR; the PSI is measured by mechanical equipment and then correlated to the PSR.

The PSR–PSI method of rating pavements became the accepted method, which was widely used until the late 1980s. During this period, all states were required to submit data on roughness/ride quality in PSR units (10). In 1988 the Federal Highway Administration (FHWA) introduced a change, requiring all states to report pavement condition in the newly developed International Roughness Index (IRI). The IRI, which was developed by the World Bank (see Figure 2.1) to minimize rating panel bias (2), represents the reaction of a typical passenger vehicle to road surface roughness. It is defined as the ratio of accumulated suspension motion (Reference Average Rectified Slope) to distance traveled of a standard quarter-car simulation (one front wheel) at a



adapted from reference 2

Figure 2.1 The IRI Scale

speed of 55 miles per hour (88.5 km/h).[1] It can also be reported as a half-car simulation (two front wheels) (11).

Based upon work by Al-Omari and Darter, the following relationships have been developed between PSR and IRI (12).

$PSR = 5e^{(c*IRI)}$	SI units	c=.226, flexible pavements
$PSR = 5e^{(-.0041c*IRI)}$	US units	c=.286, rigid pavements

The IRI is claimed to be time stable, transportable, relevant, and readily measurable (2). For a more complete description of the IRI, see Appendix 6.

2.2 Early Development of Roughness Measurement Devices

Roman road builders developed methods to measure profiles of the Appian Way more than 2000 years ago (13). The first modern profile measuring device was the viagraph, developed by Mr. J. Brown of Belfast, Northern Ireland. This device, introduced in the late 1800s, was a 12-foot (3.658m) straightedge that was drawn along the road profile. Unevenness was recorded on a strip recorder, and the degree of unevenness was given a numerical index value. The viagraph proved quantitatively that steam rollers reduced road roughness. A level of roughness of fifteen feet per mile was suggested as the standard, in what might be the earliest example of an initial ride quality specification (14).

[1] Measurements in the body of this report are expressed in English units, with metric equivalents in parentheses. Numbers in tables are generally expressed in English units only; a Conversion Table is included at the beginning of the report for the use of the reader.

The Bates profilometer was introduced in 1922. A fifty-foot-long device, it measured longitudinal profile by means of 32 bicycle wheels. It was used for a limited time, but was not well received because it was unwieldy to operate (14).

The 1920s saw the development of the Via-Log. This device, widely used by New York State highway engineers, was mounted in an automobile and provided an analog recording of the relative movement of the front axle with respect to the frame of the automobile (15). It worked well, but at a cost of $750 it was considered an expensive piece of equipment.

The Bureau of Public Roads (BPR) introduced the Roughmeter in 1941 (9). It was a single-wheel trailer that measured unidirectional vertical movements. Principally it was similar to the Via-Log, except that the leaf-sprung road wheel was independent of the vehicle and provided greater measurement consistency because all units were of identical manufacture, rather than adapted to an existing vehicle. Output was expressed in inches per mile. Because the device had an electromechanical counter, it was limited to an operating speed of about 20 miles per hour (32.18 km/h) (10). Its slow speed became a safety issue, because the roads in greatest need of roughness measurements were often the higher-speed roads. The BPR Roughmeter was later fitted with electronics to allow higher-speed operation, but its appeal gradually declined.

2.3 Current Measurement Methods and Devices

The different methods of collecting profile and roughness data have been grouped (16) into four classes of equipment as shown below:

Class	Equipment	Maximum Error	Measurement interval
I	Manual Profiling Techniques	1.5% bias; 0.3m/km =19 in/mi	< or = 1.0 ft. (0.3 m)
Example: Rod and Level			
II	Direct Profiling Equipment	5% bias; 0.7 m/km =44 in/mi	< or = 2.0 ft. (0.6 m)
Example: South Dakota Road Profiler and other profilers and profilometers			
III	RTRRM's	10% bias; 0.5-1.0 m/km =32-63 in/mi	
Example: Mays Ride Meter			
IV	Not suitable for use in collecting roughness data for FHWA Highway Monitoring System (HPMS)		

Class I includes all manual profiling techniques such as rod and level. Class II includes direct profile measuring equipment. This group also includes noncontact devices such as laser, light beam and acoustic techniques which must be kept in calibration in accordance with manufacturer's specification. Class III includes the Response Type Road Roughness Meters (RTRRM's) and is the most common equipment presently being used for extensive data collection. The RTRRM systems measure the dynamic response of a mechanical device as it travels over the roadway surface at a constant speed. These devices use a variety of displacement technologies including the use of axle/body displacement transducers and accelerometers mounted on axles and/or bodies. Such devices must be calibrated to known profiles. Traditional RTRRM's measure ARS values which make correlation to IRI very convenient. Class IV includes subjective estimations of roughness made by an observer using a descriptive scale that approximates the IRI for different road conditions and ride sensations. This method is not suitable for HPMS purpose.

2.3.1 Manual Profiling Techniques

These devices are manually operated. They measure profile to the highest level of precision and repeatability (10). These measurement devices include the following:

Survey Rod and Level

A direct way to measure the profile of a road surface is with a survey crew using precision leveling techniques. Profile levels should be taken along each wheel path at one-foot intervals. Although this method is very accurate, it is highly labor-intensive. Over 20,000 individual rod readings are required to survey a mile of two-lane road. The method is practical only over short distances, or for establishing test sections to calibrate other test equipment.

A modern digital level should be used, which is checked for accuracy both before and after use. The level rod should be equipped with a bubble level and a bar code, to be read automatically to the nearest 0.001 foot (0.305 mm). Errors in this type of leveling tend to be a combination of both random and systematic.

The rod and level is a standard to which all other profile measurement methods are compared. It is the only technique in which measurements are made with respect to a fixed reference datum.

The Straightedge

A straightedge is a simple, low-cost device that can be used to measure longitudinal profiles. Common lengths for straightedges are 10 ft. (3.048m), 12 ft. (3.658m), 15 ft. (4.572m) , 16 ft. (4.877m), and 30 ft. (9.144m). The straightedge is placed along a wheel path, and gap measurements are made at one-foot intervals. This method is time-consuming for surveys over long distances, and long straightedges are unwieldy to use and easily damaged. A straightedge cannot measure wavelengths longer than its own length, and it can distort wavelengths that are harmonics of its span (15).

An advantage of straightedge measurement is that profile irregularities are easily seen by inspection. The straightedge can also be used soon after a pavement is placed. This method is popular with paving crews to check for localized roughness around driveways, intersections, drainage structures, and at the beginning of the day cold joint.

The Face Technologies Dipstick®

This device is known as a digital incremental profiler. It is capable of collecting precision profile measurements at a higher rate than can be achieved with a conventional level and rod survey crew. The device, operated by one person, is walked along a wheel path alternately on its two feet. A sensor and pendulum determine relative readings of the road surface. The level of accuracy claimed by the manufacturer is about 0.0015 inches (0.038 mm) per individual reading (17).

While quicker than conventional leveling, this method is still slow, measuring at the rate of about 0.2 miles per hour (0.322 km/h) (14). Errors tend to be systematic and cumulative, leading to a divergence from the true profile over long distances.

2.3.2 Direct Profiling Equipment

Profilers or this type are sometimes referred to as rolling straightedges. They are calibrated to a manual profile survey. Measurements made within a system are repeatable, but measurements made with different systems are not equivalent. A strong relationship does exist between different systems, however, indicating that similar units can be calibrated against each other (18).

The devices are very good for short wavelength measurements made at high resolution, and result in low error levels (19). Actual profiles are recorded, not the response of a vehicle to the road profile. Due to varying equipment geometry, profilers amplify some wavelengths while attenuating others (3). Examples of this type of equipment are briefly discussed below.

The GM Profilometer

This device was developed in the early 1960s by Elson Spangler and William Kelly at the General Motors Research Laboratory in Warren, Michigan. It utilized two road-following wheels with linear potentiometers to measure relative vehicle frame motion and distance to the road surface. In addition, accelerometers placed over each wheel measured frame motion at low frequency (0.1 Hz). Higher frequency motion (above 2 Hz) was measured with potentiometers. Midrange measurements were made by both accelerometers and potentiometers (15).

This device was originally developed and built to collect data for use in automobile suspension design. Later, the firm of K. J. Law Engineers was granted a license by GM to manufacture and further develop the unit (14).

The K. J. Law Profilometer

This device is a derivative of the original GM profilometer described above. It uses an optical system to measure vehicle-to-pavement surface distances and accelerometers to measure body motion (14). The unit can operate at high speed—50 miles per hour (80.45 km/h) or more (20). Space for both acceleration and deceleration is needed to operate the device properly. It cannot be used on green portland cement concrete pavements.

The South Dakota Profiler

The South Dakota profiler was developed and built in-house by the South Dakota DOT in 1981. The design used laser sensors. The South Dakota profiler was well received. Eight other states built their own systems, with guidance from the South Dakota DOT. Commercially built units are now available from International Cybernetics Corporation and Roadware ARAN. More than 40 systems are now in use (7).

The California Profilograph

This device was developed by Frances Hveem around 1960. It is a 25-foot-long (7.62 m) rolling straightedge (13). Early units were fitted with 10 to 12 wheels at the ends, with a recording road wheel at the center. The profile traced by the road wheel is recorded on a strip chart at a scale of 1"=25′ horizontal; the actual variation is recorded in the vertical direction (20). Output is expressed in units of inches per mile. The device is used at walking speed, although some units are motorized for operator ease; its slow speed (about 3 miles per hour [4.827 km/h]) makes this device impractical for large-scale data collection. The device can be used on concrete pavements hours after placement and can be broken down for transport in a pickup truck or large van.

The Rainhart Profilograph

The Rainhart profilograph, manufactured by the Rainhart Co. of Austin, Texas, is similar to the California profilograph in several respects. It is about 25 feet (7.62 m) long and has twelve averaging wheels spread out over its length. Each individual wheel is less sensitive to roughness than the wheels of the California profilograph, which has tracking wheels only at the ends. The Rainhart profilograph tends to be less sensitive to short wavelength roughness, but it is claimed to be more sensitive to long wavelength roughness. While profile information produced by the California and Rainhart profilographs is similar in shape, there is a poor correlation between the two devices (21).

The Rainhart profilograph is operated at walking speed. It can be used on new pavements shortly after they are placed. Unlike the California profilograph, the Rainhart profilograph cannot be broken down for transport (14). It is fitted with removable transport wheels and must be towed between job sites.

Automatic Road ANalyzer (ARAN)

The Automatic Road ANalyzer (ARAN) is manufactured by Roadware. Most Modern ARANs use laser sensors; older ARANs (such as the NHDOT device, circa 1985) were response-type system. The ARAN is a self-contained multifunction survey vehicle with the following capabilities and features, depending on the equipment options chosen (19):

1. rut depth and transverse profile measurement with ultrasonic sensors
2. ride quality and roughness estimates via accelerometers on the rear axle
3. video of the right of way
4. shuttered video of the pavement surface, at 30 frames per second
5. onboard processor to record data
6. ultrasonic or optical sensors for longitudinal profile measurement
7. keyboards for pavement management rating

Roughness measurements are based on the IRI computed for each wheel path. The current trend is to report the average IRI measured in each wheel path at 0.01-mile (52.8-foot; 16.09 m) intervals.

It is claimed that the ARAN is capable of making detailed profile measurements at an interval of 0.33 feet (0.102 m) for both wheel paths. Accelerometers in the vehicle establish a frame of reference, and a spectrograph measures changes in distance to the road surface. Accuracy of 1 mm is claimed at operating speeds of 50 miles per hour (80.45 km/h) or more.

Advantages of this type of equipment include speed, versatility, and ease of operation. The units are expensive, however, costing $900,000 or more, depending on the capabilities and features included.

Profilometer Data Evaluation

Data generated by profilometer-type devices are processed and evaluated by means of a blanking band. In the pre-computer days, this band was prepared by scribing lines parallel to a reference line on a strip of clear acetate. The strip was used as an overlay to locate high and low points on the profilometer traces that were outside the band. The band width was used to blank out minor aberrations in the analog trace and locate "must grind" sections in portland cement concrete pavements (21). The width of the blanking band was chosen by experience and engineering judgment. Typically a 0.2-inch (5.08 mm) band was used for analysis of the California profilometer, and a 0.1-inch (2.54 mm) band was used for the Rainhart profilograph (14) (see Figure 2.2).

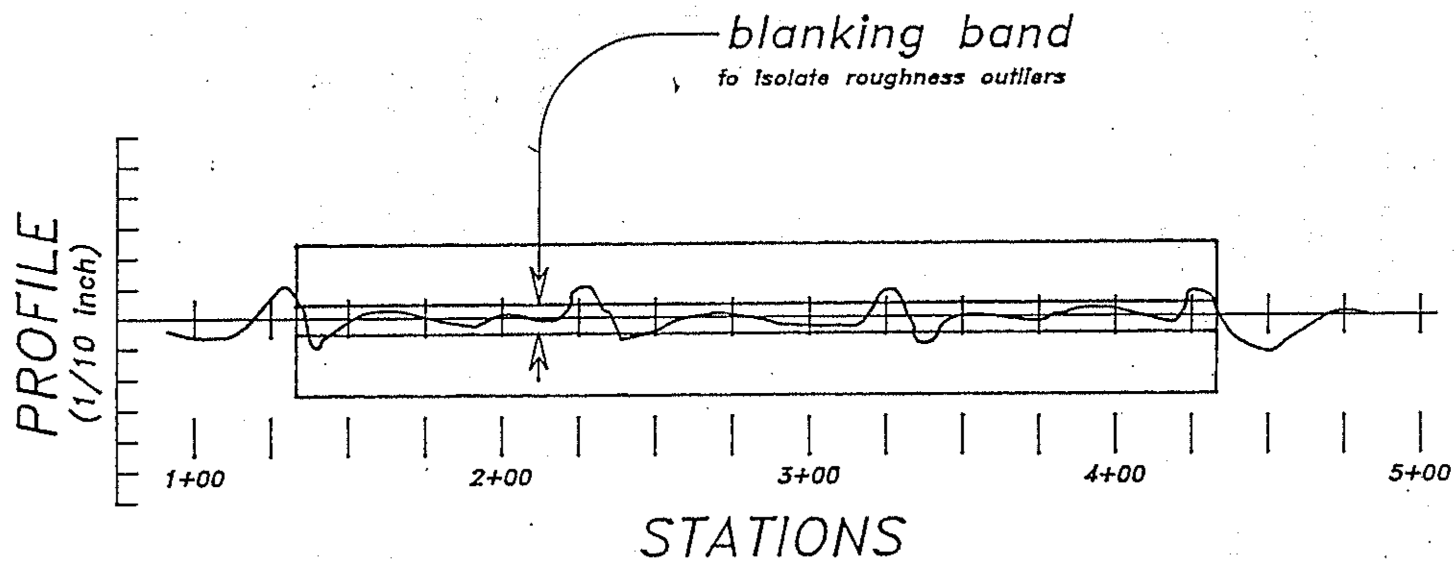


Figure 2.2 Blanking Band Applied to Profilograph Trace

Recent work by Cumbaa suggest that the use of 0.2-inch (5.08 mm) bandwidths can hide the presence of roughness that can be felt by vehicle occupants (22).

2.3.3 Response-Type Indirect Measurements

Response-type road roughness measuring (RTRRM) systems measure vehicle reactions to dynamic effects, such as chassis-to-body deflections, without measuring the surface profile (23). These devices are correlated to manual and dynamic, direct profile method surveys by means of IRI equations. Typically, this type of measurement system is capable of collecting large volumes of data at high speeds. Disadvantages include problems with calibration, dependency on the host vehicle and its characteristics, and a lack of correlation to rating panel results for surfaces other than bituminous concrete.

Road Meters

The Mays Ride Meter and the Portland Cement Association meter are examples of road meters. Both operate by measuring the vertical distances between the vehicle frame and the rear axle assembly. They have been found to be time unstable, requiring frequent calibration (15). Some roughness frequencies are amplified and some are attenuated with this type of equipment.

2.4 Paving Procedures

Large-scale paving projects undertaken by state highway agencies are generally contracted to the private sector. Work of this type is advertised and awarded to the lowest bidder meeting the specifications. Paving specifications cover such elements as scope of the project, limits of work, material specifications, compliance testing, and payment procedures. They generally do not cover such matters as equipment to be used, field procedures, and scheduling, except in a very general way. Those details are left to the contractor, who must produce a pavement that meets contract specifications and is acceptable to the public.

Some initial roughness in a new pavement or overlay can be attributed to the operations and procedures of the paver and crew at the time the pavement is placed. Factors that can influence roughness include stops and starts of the paving operation, paver speed, head of hot mix on the screed and augers, operation of the delivery vehicles, mechanical and electronic equipment failures, roller operation, and the return of traffic to a new surface. Public pressure to maintain travel and minimize trip delay has often caused state highway agencies to direct contractors to pave at night, during off-peak hours. Despite flood lighting, the ability to see the surface is not good and quality control of the paving operation is more difficult to maintain.

It is suspected that these paving procedures affect the initial roughness of new bituminous concrete pavements and overlays, but little work has been published that addresses these issues (24).

2.5 Selected Ride Quality Studies

2.5.1 Pennsylvania Transportation Institute Study

In a 1989 Pennsylvania Transportation Institute study, Kulakowski and Wambold (25) reviewed methods and equipment used by 36 SHAs in the United States for measuring the roughness of new pavements. The study revealed that many types of equipment for measuring roughness were being used in the evaluation of new pavements. The California profilograph, used by 21 SHAs, was found to be the most popular device. The Mays Meter and the Rainhart profilograph were the next most popular devices, used in 3 states. A profilometer device was used in 2 states and the Bureau of Public Roads Roughmeter was used in 1 state.

The Pennsylvania study also classified equipment into two groups: (1) devices that measure road profile and (2) devices that measure vehicle response. The California profilograph, Rainhart profilograph, and the profilometers measure road profile, while the Mays Ride Meter and BPR Roughmeter measure a vehicle's response to the road surface. These devices produce different measurements, even though the units they use are the same.

The Pennsylvania study also surveyed the blanking band measurements used by each SHA. The blanking band is used to identify the bumps and dips in the profile that must be corrected in a new wearing surface. Kulakowski and Wambold (25) discovered that the most commonly used blanking band—used in 16 states—was 0.2 inches (5.08

mm). The bumps or dips which are greater than 0.3 inches over 25 feet have to be corrected. The straightedge, used by 92 percent of the states surveyed, is employed in the field to identify these bumps and dips.

The study further determined that overall rideability and outlier measurements are the specifications used by most state highway agencies. Rideability is viewed as an aggregate, representative measure of pavement smoothness, as perceived by the road user over the entire roadway section, while outlier measurements are used to identify and correct vertical displacements (i.e., bumps and dips) at specific locations along the section.

2.5.2 Arizona Department of Transportation Study

In a study sponsored by the Arizona Department of Transportation (ADOT), Carmichael, Moser, and Hudson (26) studied techniques and devices used to measure pavement smoothness. Four devices, including the 690D Surface Dynamics (SD) profilometer, the 8300 Roughness Surveyor (RS), the Mays Ride Meter (MRM), and the California (CA) profilograph were evaluated and ranked according to their performance. These devices were tested for quality of roughness data, instrumentation precision and reliability, operating restrictions, set-up and operating complexities, equipment durability, automated data collection and processing, equipment versatility, and cost.

Quality of roughness data. The quality of roughness data were divided into three categories:

1. repeatability

2. accuracy and reproducibility
3. speed dependency

For repeatability the 690D Profilometer showed the least variation and the CA profilograph the greatest. In the accuracy category, the 8300 RS and the CA profilograph were more accurate than the MRM, and the 690D profilometer had the highest level of accuracy. As for speed dependency, the MRM roughness profile showed significant variation at different speeds. The 8300 RS showed no variation at different speeds, and the 690D profilometer and CA profilograph were operated at only one speed.

Instrumentation precision and reliability. Instrumentation precision and reliability tests focused on:

1. precision
2. reliability
3. distance accuracy
4. sensitivity to calibration

The 690D profilometer ranked the highest in precision. The 8300 RS was sensitive to temperature, but with the appropriate inputs the user could compensate for the error. The MRM was precise, but only if the speed was held constant. The least precise device was the CA profilograph because it depends on a mechanical linkage and manual data interpretation.

All devices were highly reliable, with the exception of the 8300 RS, which had frequent instrument breakdowns. As for distance accuracy, the CA profilograph gave 4 to 5 feet of error in every 1000 feet (i.e., 1.219m to 1.524 m per 304.8 m)—an undesirable level of distance accuracy. In the calibration category, the 690D profilometer is self-calibrated, while the MRM and the 8300 RS were more difficult to calibrate. The CA profilograph did not need calibration as long as it was correctly assembled.

Operating restrictions. Several parameters contribute to operating restrictions that affect the quality of the measurements. These are:

1. environmental effects
2. traffic interference
3. operating speed

Environmental effects, such as a wet pavement or very low temperature, ranked the 8300 RS last, largely because of its ultrasonic sensors. The CA profilograph and the 690D profilometer were difficult and unsafe to operate in the rain. The MRM was the least restricted by environmental factors. As for traffic interference, traffic on the roadway did not have to be rerouted for any of the devices except the CA profilograph, which also was at a disadvantage in the operating speed category. While the other devices could measure road profile at posted speed, the CA profilograph could not be used with the flow of traffic.

Set-up and operating complexities. The CA profilograph required two people to assemble and was very sensitive to steering maneuvers, which caused it to be ranked last in this category. The 690D profilometer, which required some educational background and training, ranked in the middle of the devices. The 8300 RS and the MRM were the easiest to operate and did not require much training time; consequently these devices were ranked highest.

Equipment durability. For equipment durability the 690D Profilometer ranked highest, based on experience and usage. When properly maintained and operated, the MRM and the CA profilograph ranked second. The 8300 RS ranked last because of the frequent breakdowns and equipment failures experienced during the Arizona study.

Automated data collection and processing. Automated data collection and processing were examined in terms of two criteria:

1. computer compatibility
2. availability and quality of on-board data

On both criteria, the 690D profilometer was ranked the best of all devices because its data were digitized and could either be processed using the on-board computer or downloaded to a main computer for processing. The 8300 RS was ranked second because all data were stored on a cassette tape, from which, with some work, the data could be transferred to a computer. The MRM ranked third because all information was summarized automatically. Finally, the CA profilograph ranked last because the device was not computer-compatible and it was necessary to calculate the profile index.

Equipment versatility. For equipment versatility and productivity, the 690D profilometer ranked highest because it generated digitized profile data which were the best source for calculating roughness statistics. It also required the least calibration time and experienced fewer breakdowns that the 8300 RS. The CA profilograph was the lowest ranked device because of its limited application, slow measurement speed, and time-consuming data processing.

Cost. The criterion of initial cost ranked the CA profilograph and the MRM most favorably; they were the least expensive at approximately $20,000. The 8300 RS was next, followed by the 690D profilometer, which was the highest-priced device at $250,000.

Overall, Carmichael, Moser, and Hudson (26) chose the 690D profilometer as the best device for measuring roughness. The Mays Ride Meter was in second place only because it needed regular calibration. The California profilograph was labor-intensive and slow, but was considered an acceptable device for measurement. The 8300 Roughness Surveyor required improvements in durability and reliability.

2.5.3 University of Wyoming Study

In 1995, Staigle, Ksaibati, and Adkins (27) conducted a study at the University of Wyoming that determined that straightedges and profilographs were currently the most widely used devices for assessing smoothness acceptance of new pavements. The straightedge was used by 16 SHAs and the profilograph-type device by 15. In 18 SHAs, these devices were used for determining incentive and disincentive schedules for payments on newly paved roads.

Staigle, Ksaibati, and Adkins (27) also examined the initial roughness of a pavement section to see if it had any effect on long-term performance. The University of Wyoming and the Wyoming Department of Transportation (WYDOT) examined the effect of initial smoothness of asphalt pavements on roughness measurements collected after the sections had been in service for a few years.

Test sections selected from interstate projects that were rehabilitated between 1988 and 1992 were also evaluated. Current pavement roughness data were obtained from these test sections and stored in a computerized database. A statistical analysis was performed on all data. Each project was divided into half-mile test sections, giving a total of 884 test sections. Average Daily Traffic (ADT), truck traffic, Equivalent Single Axle Loads (ESALs), and previous roughness data for these test sections were also collected.

After data collection, a comprehensive data analysis was performed. This analysis examined the relationship between initial and future (i.e., current) IRI measurements, generated a regression relationship for each chart, and performed the Mann-Whitney test on all data. The Mann-Whitney test (27) is a non-parametric test based on the rank ordering of observations.

Scatter graphs of the data were developed to see if any trends emerged. An upward trend on all asphalt test sections showed that the initial IRI measurements were correlated with future roughness values. A statistical analysis was then performed, using the Mann-Whitney test. Initial IRI measurements were statistically tested against future IRI values to determine if initially smoother pavements remained smoother over time. The Mann-Whitney test (27) indicated that the two groups (i.e., initially smoother and initially rougher) were statistically different over time, a finding that established that initially smoother sections performed better than initially rougher sections. A more recent study (28) of over 200 asphalt concrete and portand cement concrete pavement projects in 10 states tends to support the conclusions that initial smoothness may have a positive effect on future smoothness, and that higher initial smoothness may lead to longer pavement life.

2.5.4 Colorado Department of Transportation Study

The Colorado DOT (29) began to develop a ride quality specification during the 1992 and 1993 paving seasons. The specification was based on the California rolling profilograph, essentially a 25-foot (7.62 m) straightedge equipped with a transducer for measuring vertical displacement as the profilograph moves over the road surface. A blanking band of 0.1 inches (2.54 mm) was used, which is more stringent than the blanking band of 0.2 inches (5.08 mm) used by most SHAs. The 0.1-inch (2.54 mm) blanking band was chosen because low amplitude vibrations caused by the vibratory rollers during construction would not be captured with a 0.2-inch (5.08 mm) blanking band range.

Beginning in 1994 Colorado used an incentive and disincentive payment schedule on four projects. Table 2.1 summarizes the payment criteria used for all roads during the 1994 paving season. This table was developed using a 0.1 inch (2.54 mm) blanking band.

Table 2.1
1994 Smoothness Criteria
Used for All Roads During
the 1994 Paving Season in Colorado

DAPI Inches/mile	*Payment Dollars/sq-yd*
≤ 2	+0.25
> 2-3	+0.20
> 3-4	+0.15
> 4-5	+0.10
> 5-6	+0.05
> 6-7	0.00
> 7-8	-0.05
> 8-9	-0.10
> 9-10	-0.15
> 10-11	-0.20
> 11-12	-0.25
> 12	-0.25 Corrective Work

In 1995 Shuler and Horton (29) identified and reviewed perceived problems with the 1994 specification. As a result, the asphalt industry and the Colorado DOT decided to make major changes in smoothness levels and incentive and disincentive levels for each type of facility. Smoothness levels were adjusted by both industry and DOT officials for each facility. Tables 2.2-2.5 below describe the payment criteria for the four different pavement facilities. These facilities include rural interstates; urban interstates and other limited access roads; rural two-lane roads; and urban and thin, single-lift roads. Criteria for rural interstates have the most stringent smoothness requirement, while two-lane rural interstates have a lower requirement.

Shuler and Horton (29) recommend that smoothness specifications be introduced gradually to allow the contracting community to learn methods and obtain equipment necessary to achieve better riding pavements. They also believe that smoothness specifications should include incentive and disincentive clauses to encourage contractors to perform better than average work.

Table 2.2
Current Smoothness Criteria Used on Rural Interstates in Colorado (65 mph)

LPI Inches/mile	*Payment Dollars/sq. yd.*
≤ 2	+0.25
> 2–4	+0.18
> 4–6	+0.12
> 6–8	+0.06
> 8–12	0.00
> 12–14	-0.06
> 14–16	-0.12
> 16–18	-0.18
> 18–20	-0.25
> 20	Corrective Work

Table 2.3
Current Smoothness Criteria Used on Urban Interstates in Colorado (55 mph)

LPI Inches/mile	*Payment Dollars/sq. yd.*
≤ 2	+0.25
> 2–4	+0.20
> 4–6	+0.15
> 6–8	+0.10
> 8–10	+0.05
> 10–14	0.00
> 14–16	-0.05
> 16–18	-0.10
>18–20	-0.15
> 20–22	-0.20
>22–24	-0.25
> 24	Corrective Work

Table 2.4
Current Smoothness Criteria Used on Rural Two-lane Roads in Colorado (Less Than 55 mph)

LPI inches/mile	*Payment Dollars/sq. yd.*
≤ 2	+0.25
> 2–4	+0.21
> 4–6	+0.17
> 6–8	+0.12
> 8–10	+0.08
> 10–12	+0.04
> 12–16	0.00
> 16–18	-0.04
> 18–20	-0.08
> 20–22	-0.12
> 22–24	-0.17
> 24–26	-0.21
> 26–28	-0.25
>28	Corrective work

Table 2.5
Current Smoothness Criteria Used on Urban and Thin, Single Lift Roads in Colorado

Improvement %	*Payment Dollars/sq. yd.*
> 75	+0.25
> 70–75	+0.20
> 65–70	+0.15
> 60–65	+0.10
> 55–60	+0.05
> 45–55	0.00
> 40–45	-0.05
> 35–40	-0.10
> 30–35	-0.15
> 25–30	-0.20
> 20–25	-0.25
<= 20	Corrective work

2.6 Major Findings and Conclusions

The analysis of the literature on ride quality and roughness has yielded several significant findings, including the following.

- It appears that the most commonly used device to measure pavement roughness is the California profilograph (25).
- A blanking band of 0.2 inches (5.08 mm) is apparently used by most state highway agencies (25).
- Overall rideability and bump specification appear to be the two specifications used by most state highway agencies (25).
- The use of the profilometer for determining pavement surface roughness has

been gaining favor because the results of the profilometer have been found to be more accurate and reproducible than those obtained with other measurement devices (26)

- Compared with other measurement devices, the Mays Ride Meter has been found to be the least restricted by environmental factors (26).
- Application of the Mann-Whitney Test in one major study indicates that smoother sections of pavement perform better over time than rougher sections (27).
- The Kansas Department of Transportation uses a "zero" blanking band, and the Colorado Department of Transportation considers a 0.1-inch (2.54 mm) blanking band to be more effective than the 0.2 inch (5.08 mm) band used by many states (29).
- It is recommended that smoothness specifications be introduced gradually to allow the contracting community to learn methods and obtain equipment necessary to achieve better riding pavements (29).

These findings and conclusions are important for enhancing our understanding of current ride quality practices and recent studies from other agencies. This information will be helpful for establishing reasonable and up-to-date guidelines for the implementation of initial ride quality specifications.

CHAPTER 3

A REVIEW OF PAVING AND RIDE QUALITY PRACTICES

To determine the state of the art in paving and ride quality practices of state highway agencies (SHAs) in New England, a questionnaire was designed and used as a guide to conduct on-site meetings with each SHA in the region. A copy of the questionnaire appears in Appendix 1; a list of SHA personnel involved in these meetings can be found in Appendix 2. A summary of the practices reported to be in use in New England appears in Table 3.1.

In addition, the paving and ride quality practices of three other SHAs—Michigan, Texas, and Kansas—were also reviewed. This supplemental survey was conducted by telephone; the contacts are listed in Appendix 2. A summary of reported practices in these states appears in Table 3.2.

3.1 Connecticut Department of Transportation (ConnDOT)

ConnDOT uses hot mix asphalt (HMA) concrete as its primary paving material and does not require that a transfer vehicle be used. When resurfacing, ConnDOT engineers determine on-site if it is necessary to mill; if milling is found to be necessary, a depth is chosen and an HMA overlay of the desired thickness is put down.

Table 3.1 Summary of Current Paving and Ride Quality Practices in New England

AGENCY

Issues/Questions	ConnDOT	MDOT	MHD	MTA	NHDOT	RIDOT	VAOT
Who is the contact?	Keith Lane	Wade McClay	Mike Ecmecian	John McQuaid	Glenn Roberts	Lee Perkins	Duane Stevens
What type of pavement is most widely used?	BAC	BAC	BAC	BAC	BAC	BAC	BAC
Is a transfer vehicle used?	Up to the contractor	Required only for expressway	Up to the contractor	YES	Up to the contractor	Up to the contractor	Up to the contractor
Is there a ride quality spec?	NO	NO	NO	YES	YES	NO	YES
When was spec put in place?	N/A	N/A	N/A	December 1995	1995 Pilot	N/A	1995 Pilot
Is a spec being considered?	YES	YES	YES	N/A	N/A	YES	N/A
Does spec include bonuses?	YES	NO	YES	YES	YES	NO	YES
Does spec include penalties?	Not on the first few trials	NO	YES	YES	YES	NO	YES
What equipment is (or is expected to be) used to measure ride quality spec?	ARAN	ARAN Response	N/A	ICC SD Profiler	K.J. Law profilometer	ARAN	Mays meter
Is the equipment owned by the DOT?	YES	YES	NO	NO	YES	NO	YES
What roughness measures are used?	IRI (in/mile)	IRI (in/mile)	IRI (in/mile)	IRI (in/mile)	Ride number (ASTM E 1489)	IRI (in/mile)	IRI (in/mile)

Continued, next page

Table 3.1 (continued)

AGENCY

Issues/Questions	ConnDOT	MDOT	MHD	MTA	NHDOT	RIDOT	VAOT
Percentage of payment based on IRI values	IRI / % Paid < 50 110% 50 - 75 105% 76 - 90 100% > 90 penalty	N/A	See Spec.	IRI / %Paid < 50 110% 50–75 105% 76–90 100% 91–100 75% 101–120 50% >121 0%	Ride number used. Pay adjustments are linear, not stepped	N/A	IRI / %Paid < 49 110% 50 - 59 105% 60 - 69 100% 70 -82 98% 83 - 95 95% >96 90%
Is a consultant used in spec review?	NO	NO	NO	YES HNTB, PCS/LAW	NO	NO	NO
Milling limit	Determined at site	1.5" - 3" +	2.0 inches	< 3 inches	Determined at site	2 - 2.5 inches	Determined at site
What resurfacing practice is used?	HMA overlay	HMA overlay	HMA overlay	HMA overlay	HMA overlay	HMA overlay	HMA overlay
Bump size	0.3"	N/A	0.3"	0.3"	0.2"	0.4"	0.3
Length of straightedge	10'	16'	25'	10'	10'	10'	10'
Location of longitudinal profile testing	Right and left wheel path in each driving lane	Right and left wheel path in each driving lane	Right and left wheel path in each driving lane	Right and left wheel path in each driving lane	Right and left wheel path in each driving lane	Right and left wheel path in each driving lane	Axle centerline deviation
Time limit for acceptance testing	<30 days	N/A	48 hrs	0 to 24 hrs	A.S.A.P.	A.S.A.P.	14 days
Percentage of pavement segment evaluated.	100%	N/A	100%	100%	100%	samples	100% less structures

Continued, next page

Table 3.1 (continued)

AGENCY

Issues/Questions	ConnDOT	MDOT	MHD	MTA	NHDOT	RIDOT	VAOT
Who tests for smoothness during construction?	Contractor with straightedge	Contractor	Contractor	MTA with PCS/LAW	Contractor with straightedge	Contractor with straightedge	Contractor with straightedge
Who approves ride quality levels when construction is completed?	ConnDOT	Contractor	MHD	MTA	NHDOT	RIDOT	VAOT
Direction of ride quality testing	Traffic flow direction	Traffic flow direction	Traffic flow direction	Traffic flow direction	Traffic flow direction	Traffic flow direction	Traffic flow direction

Definitions:

Milling limit — The thickness that existing pavement is milled before an overlay is applied. This thickness varies from project to project and in some instances no milling is required.

Bump size — Maximum deviation in roughness profile.

Table 3.2 Summary of Current Practices for other Departments of Transportation

	AGENCY		
	KANSAS DOT	MICHIGAN DOT	TEXAS DOT
Issues/Questions			
Who is the contact?	Roy Rissky	George Erickson	Gary Graham
What type of pavement is most widely used?	BAC and PCC	BAC and PCC	BAC and PCC
Is a transfer vehicle used?	YES	YES	YES
Is there a ride quality spec?	YES	YES	YES
When was spec put in place?	1990	N/A	1993
Is a spec being considered?	N/A	N/A	N/A
Does spec include bonuses?	YES	YES	YES
Does spec include penalties?	YES	YES	YES
What equipment is used to measure ride quality spec?	CA profilograph	GM Type Rapid Travel profilometer and CA profilograph	profilograph
Is the equipment owned by the DOT?	YES	YES	YES
What roughness measures are used?	PI (in/mile)	RQI and PI (in/mile)	PI (in/mile)

Continued, next page

Table 3.2 (continued)

AGENCY

Issues/Questions	KANSAS DOT	MICHIGAN DOT	TEXAS DOT
Percentage of payment based on IRI values	PI used. See Spec.	PI used. See Spec.	PI used. See Spec.
Is a consultant used in spec review?	NO	YES	YES
Milling limit	Determined at Site	1.25" +	Determined at Site
What resurfacing practice is used?	HMA Overlay	HMA Overlay	N/A
Bump size	0.4"	0.3"	0.3"
Length of straightedge	10'	10'	10'
Location of longitudinal profile testing	3' from each lane edge	3' from each lane edge	3' from each lane edge
Time limit for acceptance testing	< 48 hrs	A.S.A.P.	A.S.A.P.
Percentage of pavement segment evaluated.	100%	100%	100%

Continued, next page

Table 3.2 (continued)

AGENCY

Issues/Questions	KANSAS DOT	MICHIGAN DOT	TEXAS DOT
Who tests for smoothness during construction?	Contractor with straightedge	Contractor	Contractor
Who approves ride quality levels when construction is completed?	DOT	DOT	DOT
Direction of ride quality testing	Traffic Flow Direction	Traffic Flow Direction	Traffic Flow Direction

Definitions:

Milling limit — The thickness that existing pavement is milled before an overlay is applied. This thickness varies from project to project and in some instances no milling is required.

Bump size — Maximum deviation in roughness profile.

ConnDOT is currently developing and implementing a ride quality specification, a preliminary version of which can be found in Appendix 3.

ConnDOT has two automated road analyzing devices (ARANs) and a 25′ (7.62 m) California profilograph. The ARAN, mounted on the front of a van (as can be observed in Figure A4.2 in Appendix 4), uses laser and acoustic technologies. It is equipped with a video camera to record the texture of the road surface and other road features, as shown in Figure A4.1 in Appendix 4. The ConnDOT data processing and recording center can be seen in Figures A4.1 and A4.3. The California profilograph is 5 to 7 years old and has experienced limited use on a small number of projects since the purchase of the two ARANs. The ARANs are relatively new and will be used as the primary devices for initial ride quality measurement.

Contractors, who are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. After the completion of construction, it is anticipated that ConnDOT will use the ARAN to approve the contractor's work. Smoothness levels must comply with ConnDOT written agreements that are set before construction. Initial ride quality data are to be collected within 30 days after the completion of all pavement operations. Measurements are to be recorded for the entire length of a project and to be taken in the direction of traffic, in the right and left wheel paths in each driving lane. Measurements are recorded in international roughness index (IRI) levels, expressed in units of inches per mile.

Payment for each job is based on the IRI scale. Initially the department does not expect to assess penalties for a job completed by a contractor at less than desired smoothness levels; however, the department does intend to pay bonuses for exceptionally low roughness levels. The following pay scale, based on ARAN-recorded IRI levels, determines the percentage that the contractor is paid.

IRI	Percent Paid
< 50	110 %
50 – 75	105 %
76 - 90	100 %
> 90	penalty

3.2 Maine Department of Transportation (MDOT)

Bituminous asphalt concrete (BAC) is used as the primary material for MDOT paving jobs. Portland cement concrete (PCC) has not been used by the MDOT since the 1970s. Resurfacing projects generally require a milling depth between 1 1/2" (38.1 mm) and 3" (76.2 mm) for most interstate highways, and HMA overlays are used. The MDOT requires the use of transfer vehicles only for expressway paving operations, although some contractors choose to use them for other surfaces as well.

The contractor is responsible for maintaining a level of smoothness that is acceptable to the state agency during and after paving operations. Maine DOT does not test for initial ride quality; it uses its response-type ARAN only to test current road surfaces to determine if the roadway needs improvement. The response-type

ARAN has replaced the Mays Meter that was once used by this department. Maine DOT's ARAN is classified as a response-type road roughness system. This ARAN differs from ConnDOT's device in that it uses accelerometers mounted on the axle of the vehicle to measure roughness. The MDOT is considering the purchase of a newer version of the ARAN that uses laser and acoustic techniques, such as the one used by ConnDOT.

3.3 Massachusetts Highway Department (MHD)

MHD has recently developed a draft ride quality specification, which can be found in Appendix 3. (Note: The draft specification is currently under review and is subject to updating). The MHD uses bituminous asphalt concrete as the primary material for all paving jobs. Resurfacing projects generally require a milling depth of 2" (50.8 mm), and HMA overlays are used. The MHD does not require the use of a transfer vehicle during paving operations.

Initial ride quality data are collected within 48 hours after the completion of all pavement operations. The entire project is divided into sections, and measurements are recorded for each section. The measurements are taken in the direction of traffic flow, in the right and left wheel paths in each lane. Measurements are recorded in international roughness index (IRI) levels, expressed in units of inches per mile.

Payment for each job is based on the IRI scale. The department pays both bonuses and penalties for jobs completed by contractors. A pay scale determines the percentage that the contractor is paid, based on IRI levels.

3.4 Massachusetts Turnpike Authority (MTA)

MTA uses hot mix bituminous asphalt concrete as its primary paving material. Unlike other SHAs, it requires that a transfer vehicle be used, having learned that the use of a transfer vehicle can improve pavement smoothness. When resurfacing, MTA engineers determine the milling depth for the project, which usually amounts to less than 3 inches (76.2 mm), and an HMA overlay of the desired thickness is then put down. The MTA has developed a ride quality specification, which has been in use since December 1995. A copy of the ride quality specification is in Appendix 3.

Contractors, who are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. However, the MTA measures smoothness levels throughout the project, using an ICC SD Profiler. Upon project completion, the MTA measures smoothness over the entire length of the project less than 24 hours after paving operations have ceased. Measurements are taken in the direction of traffic flow, in the right and left wheel paths. Measurements are recorded in international roughness index (IRI) levels, expressed in units of inches per mile.

Payment for each job is based on the IRI scale. The MTA pays both bonuses and penalties for jobs completed by contractors. The pay scale summarized below determines the percentage that the contractor is paid, based on IRI levels recorded by the ICC SD Profiler.

IRI	Percent Paid
< 50	110 %
50 – 75	105 %
76 – 90	100 %
91 – 100	75 %
101 – 120	50 %
> 121	0 %

3.5 New Hampshire Department of Transportation (NHDOT)

NHDOT uses hot mix bituminous asphalt as its primary paving material. The use of a transfer vehicle is left up to the contractor. Resurfacing projects may or may not require milling; the determination is made on-site by an NHDOT engineer, and an HMA overlay of the desired thickness is used. NHDOT introduced a pilot ride quality specification in 1995 and is continuing implementation over a five-year period. The specification is part of the department's QC/QA specification for hot bituminous pavement, which is based on random sampling and statistical analyses.

NHDOT has found that the K.J. Law profilometer, which uses infrared sensors mounted on the front of the vehicle (see Figure A4.7), is the most accurate and repeatable device for measuring initial ride quality. Unlike other devices used in New England, the K.J. Law profilometer measures smoothness using both the IRI scale and the ASTME 1489 Ride Number (RN). The NHDOT specification is based on the RN, which the Department has found to have a closer correlation to mean panel ratings than IRI. The data processing unit is different from that used in the ARAN, as can be seen in Figure A4.8.

Contractors, who are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. NHDOT tests smoothness levels on new pavements during construction, using the profilometer after all paving operations have been completed.

The Ride Number is measured for the entire length of a project and is reported in 0.1-mile increment. The measurement is taken in the direction of traffic flow, in the right and left wheel paths in each driving lane. The department uses linear pay adjustments, as can be seen in the pilot specification in Appendix 3.

3.6 Rhode Island Department of Transportation (RIDOT)

RIDOT uses hot mix bituminous asphalt as its primary paving material. Use of a transfer vehicle is up to the contractor. When resurfacing, the agency generally requires a milling limit of between 2 and 2.5 inches (i.e., between 50.8 and 63.5 mm) and then an HMA overlay of the desired thickness is put down.

RIDOT does not own or operate a ride quality measuring device, but it does own the ARAN hardware to evaluate the data. Testing is performed every two years by a consulting firm, operating an ARAN that uses laser and acoustic techniques. RIDOT is currently developing and implementing a ride quality specification.

Contractors, who are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. Smoothness levels must comply with RIDOT written agreements that are set before construction.

Measurements are recorded for the entire length of the project in the direction of traffic flow, in the right and left wheel paths in each driving lane. Measurements are recorded in international roughness index (IRI) levels, expressed in units of inches per mile. RIDOT has no bonus or penalty payment schedule.

3.7 Vermont Agency of Transportation (VAOT)

The VAOT uses hot mix bituminous asphalt concrete as its primary paving material. The use of a transfer vehicle during paving operations is up to the contractor. Milling depth is predetermined and is put on contract plans. Most paving treatments involve a leveling course and a very thin overlay.

VAOT measures initial ride quality with the Mays Ride Meter device (see Figure A4.9). This device is a response-type road roughness system mounted on a trailer and pulled by a van owned by the agency. The data processing center is a laptop computer, as can be seen in Figure A4.10. VAOT is currently developing and implementing a ride quality specification.

Contractors are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. Ride quality acceptance data are collected within two weeks of the completion of all pavement operations. Measurements are calculated using the international roughness index, recorded from readings taken from the axle centerline deviation for the entire length of a project.

Payment for each job is based on the IRI scale. The VAOT pays both bonuses and penalties for jobs completed by contractors. The summary table below is a representation of the specification that determines the percentage that the contractor is paid, based on IRI levels recorded by the Mays Ride Meter.

IRI	Percent Paid
< 49	110 %
50 – 59	105 %
60 – 69	100 %
70 – 82	98 %
83 – 95	95 %
> 96	90 %

3.8 Other State Departments of Transportation

Kansas. The Kansas Department of Transportation (KDOT) uses both hot mix bituminous asphalt and portland cement concrete in paving and requires the use of a transfer vehicle. When resurfacing, KDOT engineers determine on-site the appropriate depth, and then an HMA overlay of the desired thickness is put down. KDOT has written ride quality specifications for both paving practices, which have been in use since 1990. The specification discussed here, which can be seen in Appendix 3, refers to the hot BAC method, which is relevant to paving practices in New England.

Contractors, who are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. Initial ride quality data are to be collected less than 48 hours after the completion of all pavement operations. KDOT uses a 25′ (7.62 m) California profilograph that responds to the pavement's vertical displacement, called the profile of the roadway. The information is gathered in 0.1-mile (0.161 km) sections and is recorded as a profile index (PI) expressed in inches/mile. Two runs are made at a distance of 2 to 3 feet (0.610 m to 0.914 m) from each lane edge, and the data are collected and reviewed. The average profile for each section is determined, and the contractor's price is adjusted according to the following scale.

Profile Index (inches/mile)	Price Adjustment (dollars)
< 7.0	+ 152.00
7.1 – 10.0	+ 76.00
10.1 – 40.0	0.00
> 40.1	- 2.03

Michigan. The Michigan Department of Transportation (MiDOT) uses both hot mix bituminous asphalt and portland cement concrete in paving and requires the use of a transfer vehicle. Resurfacing projects generally require a milling depth of greater than 1.25 inches (31.75 mm); following milling an HMA overlay of the desired thickness is put down.

MiDOT has a 25′ (7.62 m) California profilograph and a GM Type Rapid Travel profilometer. Initial ride quality specifications have been written for both paving practices. The specification discussed here refers to the hot BAC method, with measurements taken with the GM Type device, which is relevant to paving practices in New England. The MiDOT initial ride quality specification can be found in Appendix 3.

The GM Type Rapid Travel profilometer is more frequently used than the 25′ (7.62 m) California profilograph. It is similar to the laser-based profilometer that NHDOT uses. The GM Rapid Travel profilometer expresses the ride quality of a pavement as ride quality index (RQI) units or inches per mile. The RQI is a measurement of the true profile of the roadway; this indicator selects statistical properties that relate to perceived vehicle user response (3).

Initial ride quality data are collected less than 24 hours after the completion of all pavement operations. As an incentive for contractors to develop a smooth riding pavement, MiDOT uses a pay scale that varies according to different levels of initial ride quality. The payment scale can be seen in the MiDOT specification in Appendix 3.

Texas. The Texas Department of Transportation (TXDOT) uses both hot mix bituminous asphalt and portland cement concrete in paving and does not require the use of a transfer vehicle. Resurfacing projects generally require a milling depth that is determined on-site by a TXDOT engineer. TXDOT has written a ride quality specification to satisfy all profilographs; this specification has been in use since 1993. The specification discussed here refers to the hot BAC method and can be found in Appendix 3.

Contractors, who are responsible for acceptable smoothness levels during construction, measure initial ride quality using a straightedge. Initial ride quality data are to be collected less than 24 hours after the completion of all pavement operations. The profilograph resembles that of the KDOT in that it responds to the pavement's vertical displacement and thus records a profile of the roadway.

The contractor must test 0.1-mile (0.161 km) sections of the project using a 25′ (7.62 m) California profilograph, or a similar type of profilograph, yielding a profile index (PI) expressed in inches per mile. Two runs are made at a distance of 2 to 3 feet (0.610 m to 0.914 m) from each lane edge, and the data are collected and reviewed. The average profile for each section is determined, and the contractor's price is adjusted according to the scale shown in Appendix 3.

3.9 Summary

Based on a review of ride quality assessment and paving practices of the SHAs in New England, it has been concluded that:

- The primary paving practices being employed by SHAs in New England include the use of a hot mix asphalt (HMA) wearing surface.
- ConnDOT, MHD, MTA, NHDOT, and VAOT are all in the process of implementing a specification to be used on HMA pavements.
- ConnDOT and RIDOT all intend to use an ARAN to analyze pavement smoothness as part of their ride quality specification; NHDOT uses a KJ Law Profilometer and MTA uses an ICC SD Profiler.
- ConnDOT, MDOT, MHD, MTA, RIDOT, and VAOT all measure pavement smoothness using the IRI scale; NHDOT uses the Ride Number (ASTM E 1489).
- ConnDOT, MHD, MTA, NHDOT, and VAOT include or intend to include bonuses in their specification.
- MHD, MTA, NHDOT, and VAOT include or intend to include penalties in their specification.
- Many SHAs outside of New England measure pavement smoothness using

a response type device.

- SHAs outside of New England tend not to use the IRI as an initial ride quality measure.

CHAPTER 4

A COMPARATIVE STUDY OF RIDE QUALITY MEASURING DEVICES

4.1 Introduction

The state highway agencies (SHAs) in New England use several different devices to measure road profiles for the purpose of assessing ride quality. These devices use different sensor types, based on ultrasonic, laser, or optical systems. Questions have been raised about the accuracy and precision of these devices with respect to such variables as speed, surface texture, surface type, and climate conditions.

To address some of these questions, a study of different devices used by the SHAs in New England was conducted. Two test sites were selected in Worcester, Massachusetts, on which participating SHAs were invited to run their devices. FACE Dipstick® measurements were taken at both sites to use as "ground truth" values.

The primary objectives of this study were to:

- assess accuracy by comparing the devices to the dipstick
- assess precision by comparing the standard deviation of results produced by the devices on replicate runs on the same site
- compare the performance of the devices with one another
- study the effect of device speed on data collection
- compare the effect of different device sensor types on data collection and interpretation

4.2 Site Selection

The study was designed to be conducted on a relatively smooth pavement or a newly paved surface in Worcester, Massachusetts. Two sites were selected on Airport Drive in Worcester. Figure 4.1 shows a map on which the location of the sites is indicated together with a photograph of the test site. The two sites, Airport Drive North and Airport Drive South, are designated in this study and report as the North and South. The following is a summary of the criteria that were used to select the sites:

- IRI values within 70 to 180 in/mile (1.105 to 2.842 m/km)
- total length preferably 0.2 miles (0.322 km) with enough acceleration and deceleration areas
- relatively flat surface not to exceed 3% grade
- speed limit at least 30 mph (48.27 km/h)
- site should not contain bridges or intersecting roads, potholes, sudden changes in grade, curvature, or excessive distress in wheel paths
- ease of traffic control and safety

4.3 Data Collection and Pavement Profiling Using the Dipstick

A Face Dipstick 2000 model (walking style) was used in this study. The manufacturer's software was used to collect and process the data. Calibration of the dipstick followed manufacturer-recommended procedures. Additional information on

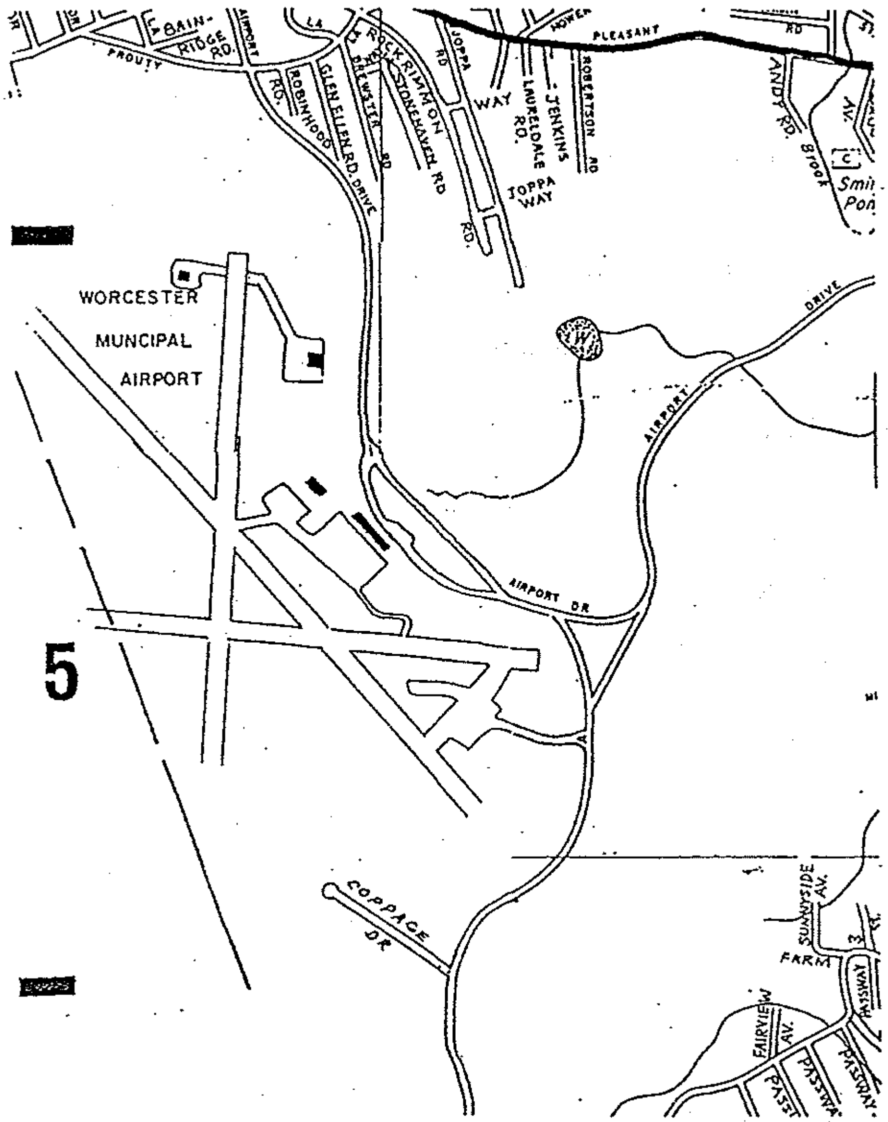


Figure 4.1 The Location of Selected Sites

the Face Dipstick 2000 model is provided in the equipment section of this report. Figure 4.2 shows photographs of the station marking operation and dipsticking.

In order to verify the accuracy of the data collection using the Dipstick, closure error calculations were performed and should agree within 0.1%.

4.4 Data Collection Procedures

Device operators were instructed to follow their normal operating procedures when collecting data, including the following:

- perform customary calibration diagnostics before testing
- test on dry pavement
- achieve constant speed and begin data collection at starting flag
- maintain constant speed over test section
- follow wheel path line markers
- decelerate after crossing the finish flag
- test at 30 and 40 mph (48.27 and 64.36 km/h) and obtain 5 error-free runs at each speed
- data are to be submitted in IRI statistic values averaged over a maximum of 0.01 miles (0.016 km)
- data may be submitted in metric or English units

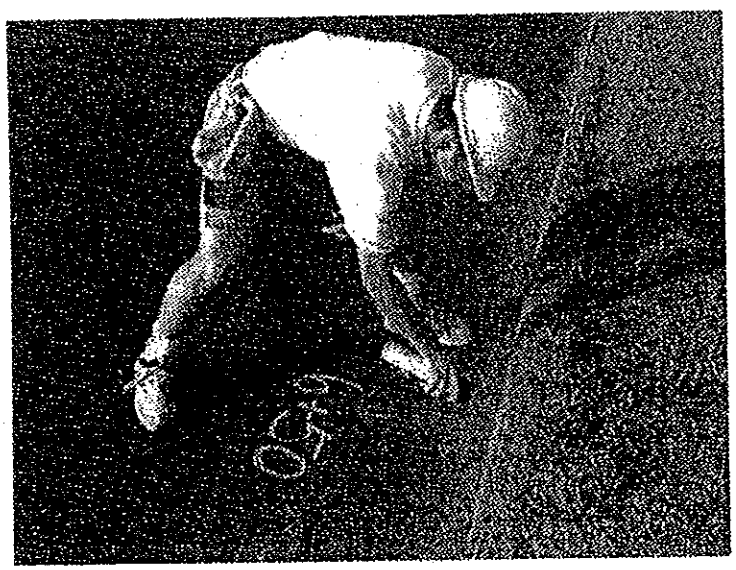
4.5 Participating SHAs and Equipment

SHAs from Connecticut, Massachusetts, New Hampshire, and Vermont participated in this study. In all, five devices were examined, including three ARANs

Worcester Polytechnic Institute
DIPSTICK

Measuring using dipstick

Calibrating dipstick



Stationing

Stationing

(Van 5 and Van 6 from Connecticut and one ARAN from Massachusetts), one K.J. Law T6500 profilometer (New Hampshire), and one Mays Ride Meter (Vermont). Images of these devices are provided in Appendix 4.

4.6 International Roughness Index (IRI) Statistic

The IRI statistic was selected as the vertical profile summary statistic parameter for comparison. The IRI is based on the World Bank Technical Report No. 46 and is described in more detail in Appendix 6.

4.7 Results

Average IRI values. The IRI values for each wheel path, each SHA device, the North and South sites, and both test speeds are presented in Figure 4.3a-d in Tables 4.1-4.11.[2] A summary of average IRI values and standard deviations for the two sites, all devices, and both test speeds is presented in Table 4.10 (metric units) and 4.11 (English units). Only one speed (~35 mph; 56.32 km/h) is provided for Vermont's Mays Meter due to calibration settings and site speed limitations. The FACE Dipstick IRI values given in these tables correspond to the value obtained from a single run.

The average IRI values and standard deviations for the profilers was computed by averaging the data for the submitted runs. The standard deviation shown in the columns adjacent to the IRI values is an indication of the variability of the profile along the segment length. (Note: This standard deviation is not associated with repeatability at this time). It is a common observation that the standard deviation within runs will be

[2] Tables referred to in this chapter appear at the end of the chapter.

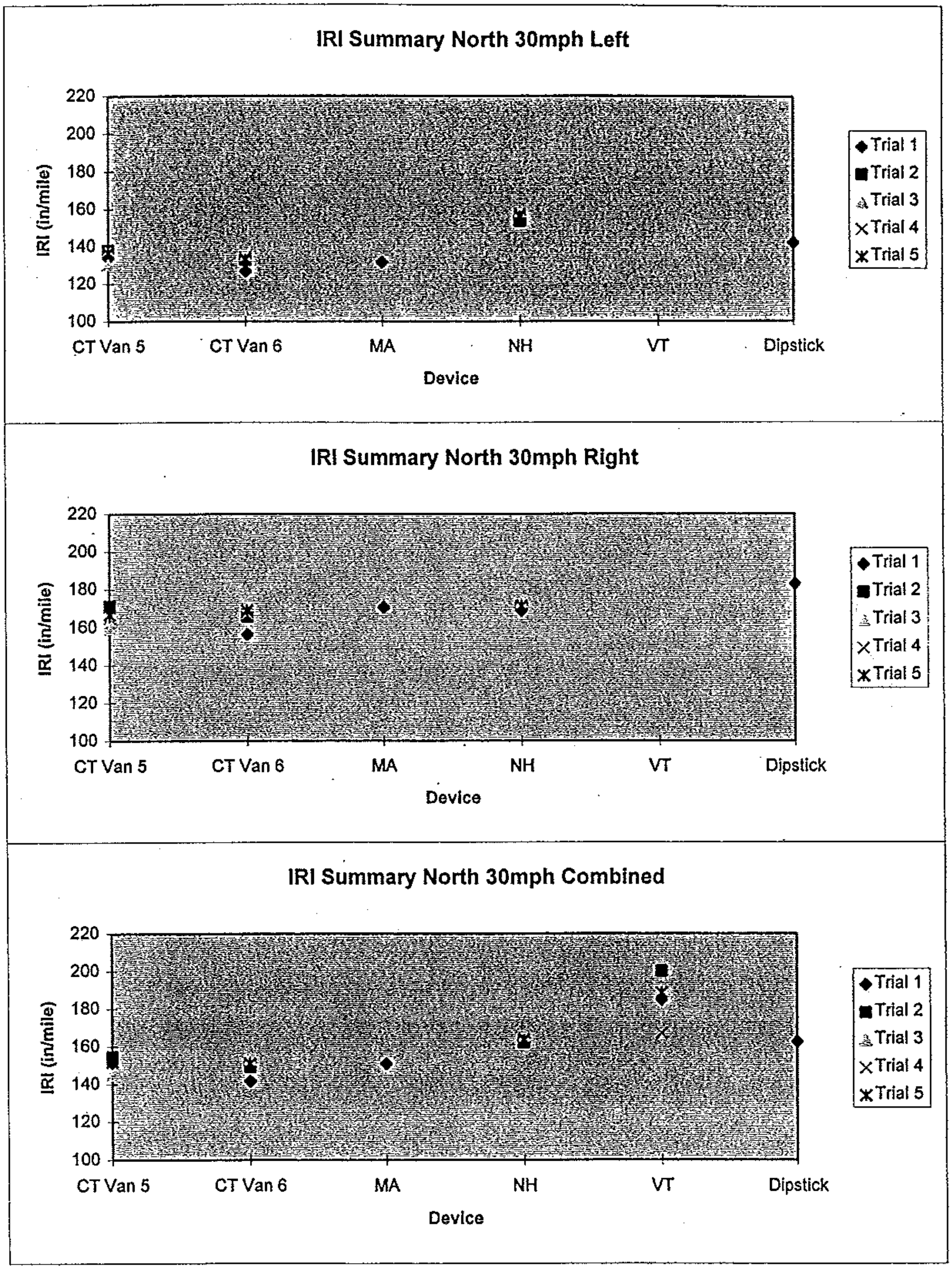


Figure 4.3a The IRI Values (North 30mph)

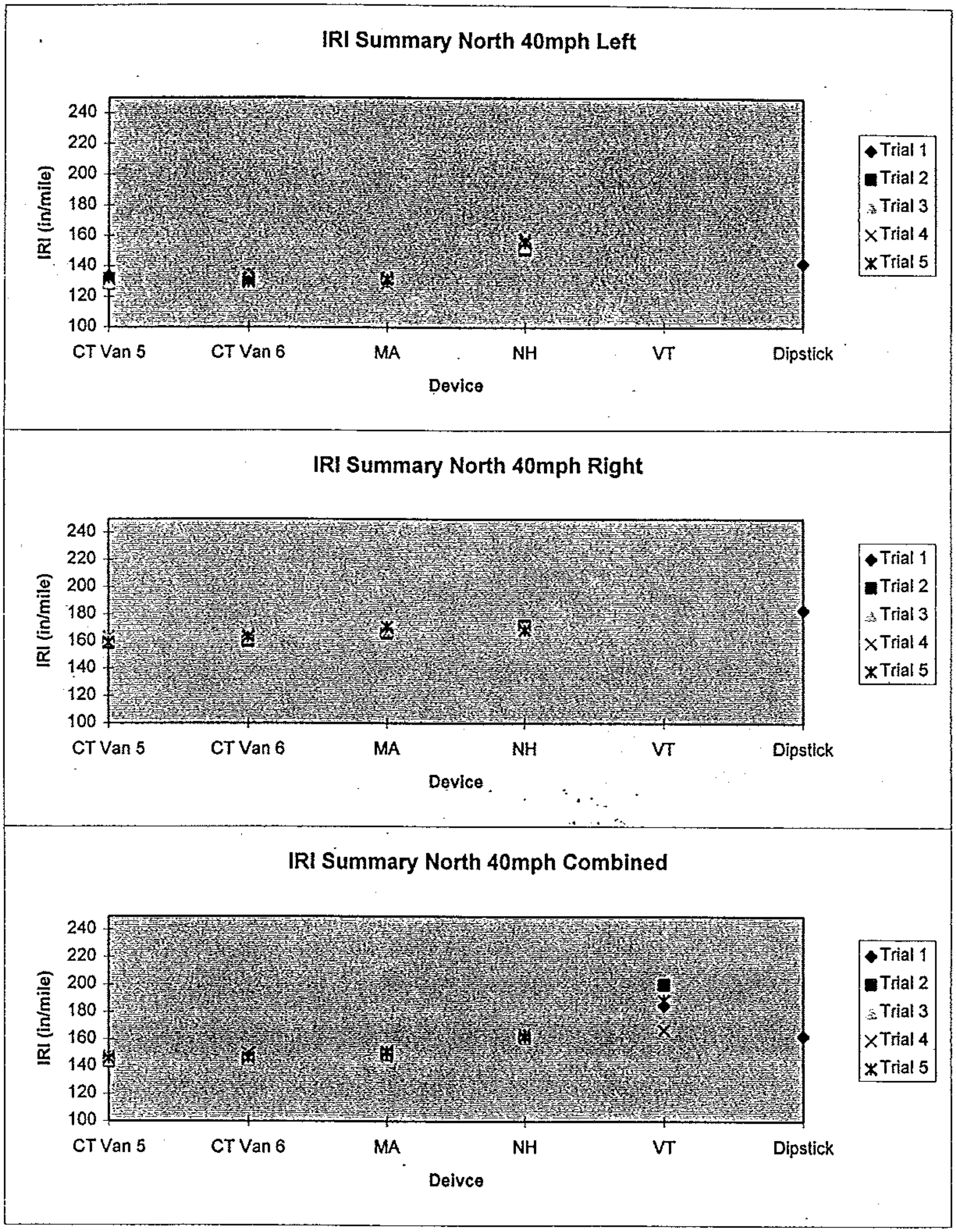


Figure 4.3b The IRI Values (North 40mph)

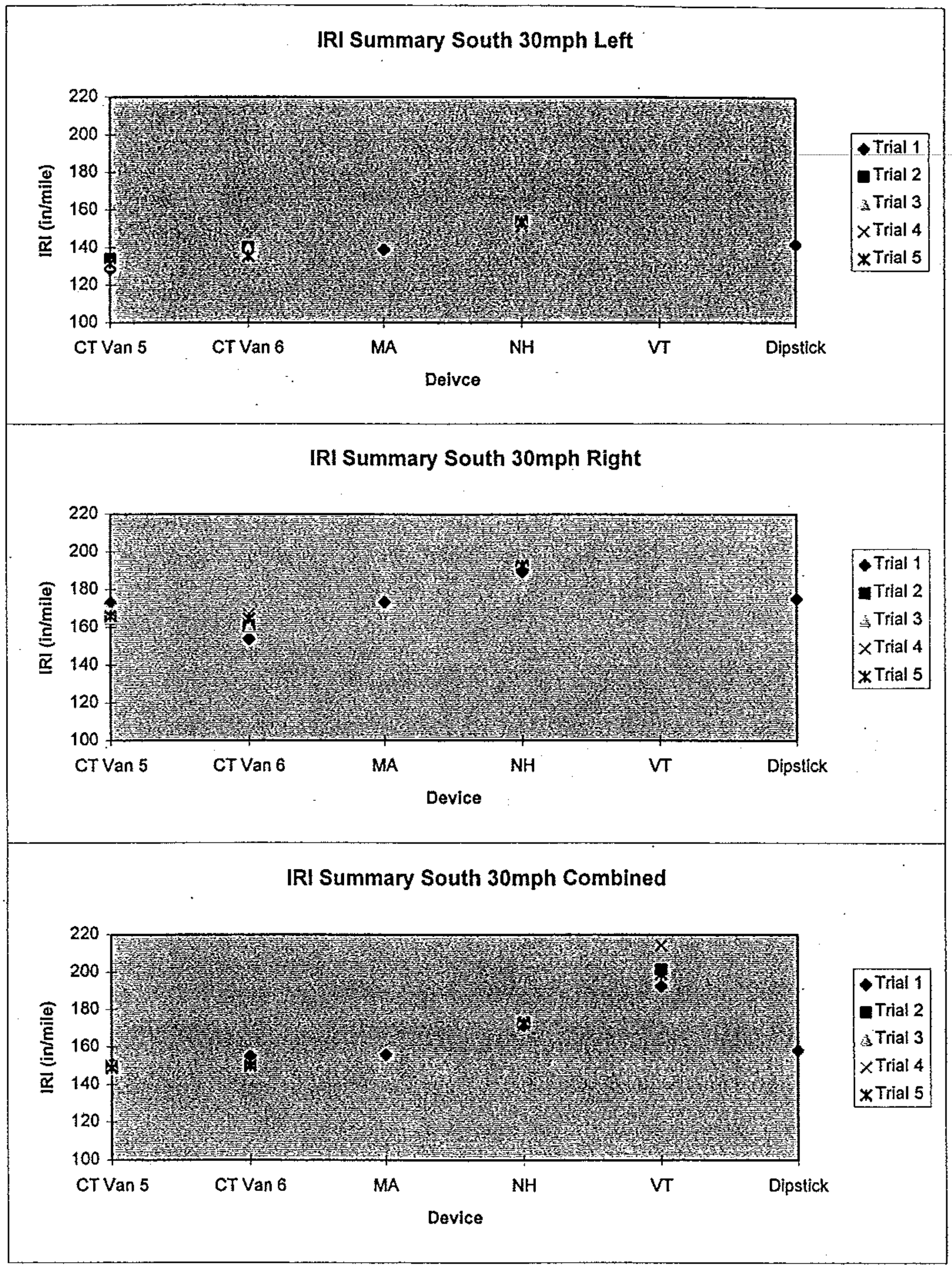


Figure 4.3c The IRI Values (South 30mph)

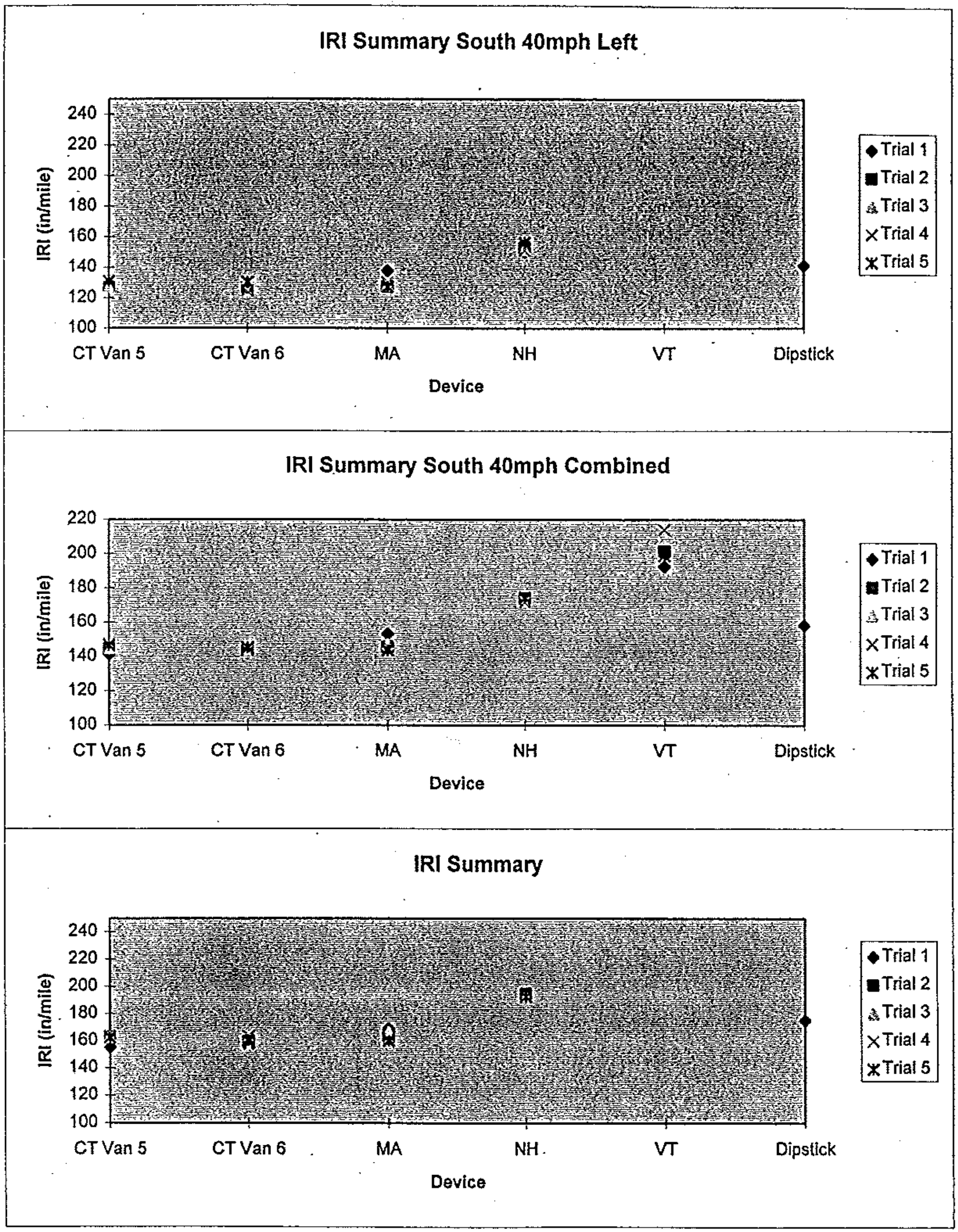


Figure 4.3d The IRI Values (South 40mph)

different for different devices. It is not clear at this point if the difference is attributed to sensor type or the filtering process during parameter calculations.

Comparison between profiler and dipstick IRI values. The vertical profile generated using the dipstick is usually assumed to be an accurate representation of the pavement profile. The differences between the IRI values obtained with each profiler and with dipstick (average device IRI minus average dipstick IRI) for both sites and test speeds are provided in Table 4.12. In general the ARAN profilers had average IRI values lower than those obtained with the dipstick. Average IRI values reported by the K.J. Law profilometer were mostly higher than those obtained with the dipstick. Similarly, the Mays Meter IRI values were consistently higher than the dipstick IRI.

Device comparisons. A comparison of IRI values obtained with all the devices is shown in the symmetrical matrix of Tables 4.13 and 4.14. Values for the different test speeds are combined, and each cell shows the difference in average IRI between each pair of devices. The values in the diagonal cells, in which each device is arrayed against itself, are of course zero.

Effect of test speed on IRI. The effect on average IRI of the speed at which testing was conducted was investigated by computing, for each device and site, the ratio between the average IRI obtained at the slower speed and the average IRI obtained at the faster speed. Table 4.15 shows these ratios for both sites and for individual and combined wheel paths, calculated as the average IRI at 30 mph (48.27 km/h) divided by the average IRI at 40 mph (64.36 km/h). Generally the ratio was close to 1.00 for most profilers and devices. (Since IRI data were gathered at only one test speed for the Mays Meter, a speed comparison was not made for that device.)

Effect of sensor type on IRI. The effect of sensor type was investigated by comparing the average IRI values obtained by all profilers that use laser sensors with the average values obtained by the New Hampshire device (the only profiler with an optical sensor). The results are shown in Table 4.16 . The laser sensors included all ARAN profilers (Connecticut Van 5 and Van 6 and the Massachusetts ARAN). The optical sensor was the K.J. Law profiler. The Mays Meter, a response type profiling device, is also included in the table for comparison.

Precision and bias. Precision (repeatability) is described by ASTM E117 as a generic concept related to the closeness of agreement between test results obtained from a measurement process conducted more than once under prescribed like conditions. The precision of a device at a test site at each speed may be evaluated by computing the standard deviations of the IRI values obtained from all replicate runs. The standard deviations for all profilers are given in Table 4.17. The standard deviation for repeat runs by each device varies between 1 and 5 in/mi. IRI units (0.016 to 0.079 m/km).

Accuracy (bias) is described by ASTM E117 as the closeness of agreement between the accepted reference value and the average of a large set of test results obtained by the repeated application of the test method. In our study, the IRI values obtained from the dipstick were considered the reference values, against which the average IRI values for each profiler at each test site and each test speed was compared. Average IRI value correspond to the results from a set of tests. For each profiler, accuracy was calculated, through straightforward subtraction, as the difference between the average profiler IRI and the dipstick IRI.

These results, presented in Table 4.18, show a wide range of values for each profiler at each site and speed. Obtaining a single value that adequately defines the accuracy of a profiler for all pavement types and speed conditions is not realistic. For this study, a measure of accuracy for each profiler was computed as the average difference between the profiler IRI and dipstick IRI obtained at combined speeds (30 mph and 40 mph; 48.27 km/h and 64.36 km/h) at each site. Table 4.18 shows the results computed for all devices.

Regression analysis between dipstick IRI and profiler IRI. A regression analysis was performed to estimate the correlation between SHA device IRI and dipstick IRI. The IRI values obtained for each of the five trials, were normalized by the corresponding dipstick IRI values. Each of the five device IRI values are plotted against the corresponding normalized value. A least squared regression line is plotted through the points and the correlation (R^2) value is calculated. Regression analyses for all devices, wheel paths, North and South sites, and speeds are presented in Figure 4.4 a-o. Based on low R^2 values, there appears to be no correlation between device IRI and predicted dipstick IRI.

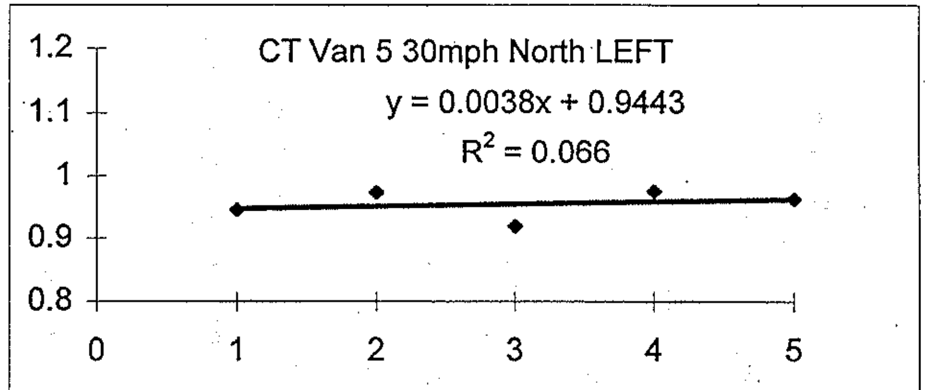
4.8 Summary of Findings

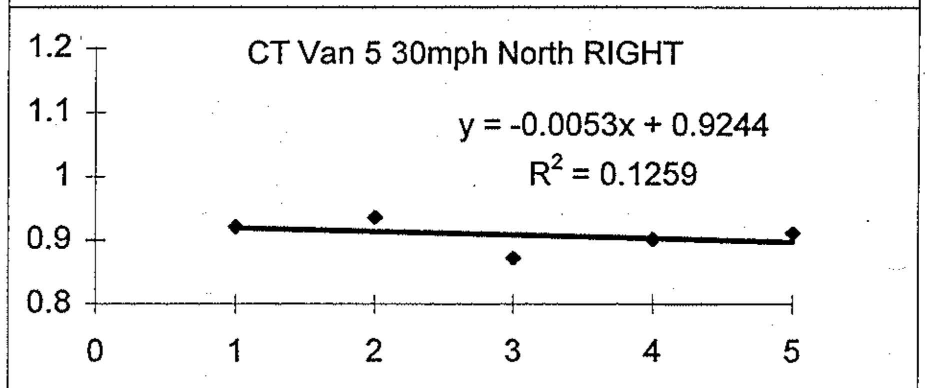
Average IRI values and standard deviations. The IRI statistic was used in this study as a smoothness parameter to compare the various profiling devices. A number of trends and correlations can be established from the data. The IRI appears to be a good

CT VAN 5 ~30mph		
LEFT	Ratio	IRI
1	0.945768688	134.11
2	0.973906911	138.1
3	0.919605078	130.4
4	0.975599436	138.34
5	0.963963329	136.69
$y = 0.0038x + 0.9443$		
$R^2 = 0.066$		

CT VAN 5 ~30mph		
RIGHT	Ratio	IRI
1	0.921022448	168.63
2	0.935660058	171.31
3	0.872303239	159.71
4	0.901523841	165.06
5	0.911409689	166.87
$y = -0.0053x + 0.9244$		
$R^2 = 0.1259$		

CT VAN 5 ~30mph		
COMBINED	Ratio	IRI
1	0.931794398	151.37
2	0.952293013	154.7
3	0.892951677	145.06
4	0.933825793	151.7
5	0.934318252	151.78
$y = -0.0013x + 0.9331$		
$R^2 = 0.0095$		





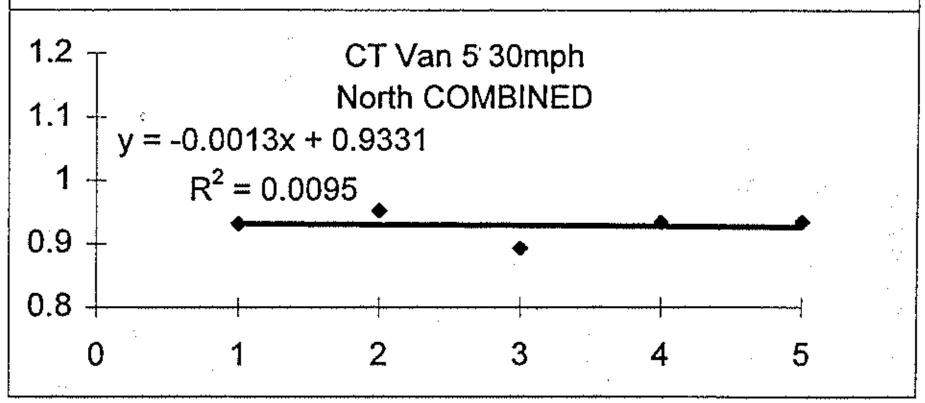


Figure 4.4a The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 North 30mph) IRI

CT VAN 5 ~40mph		
LEFT	Ratio	IRI
1	0.94048	133.36
2	0.906559	128.55
3	0.911989	129.32
4	0.928914	131.72
5	0.931241	132.05
y = 0.0004x + 0.9227		
R^2 = 0.0019		

CT VAN 5 ~40mph		
RIGHT	Ratio	IRI
1	0.875908	160.37
2	0.866678	158.68
3	0.880004	161.12
4	0.893113	163.52
5	0.870555	159.39
y = 0.0016x + 0.8725		
R^2 = 0.0593		

CT VAN 5 ~40mph		
COMBINE	Ratio	IRI
1	0.904094	146.87
2	0.884087	143.62
3	0.893937	145.22
4	0.90871	147.62
5	0.897014	145.72
y = 0.001x + 0.8944		
R^2 = 0.0303		

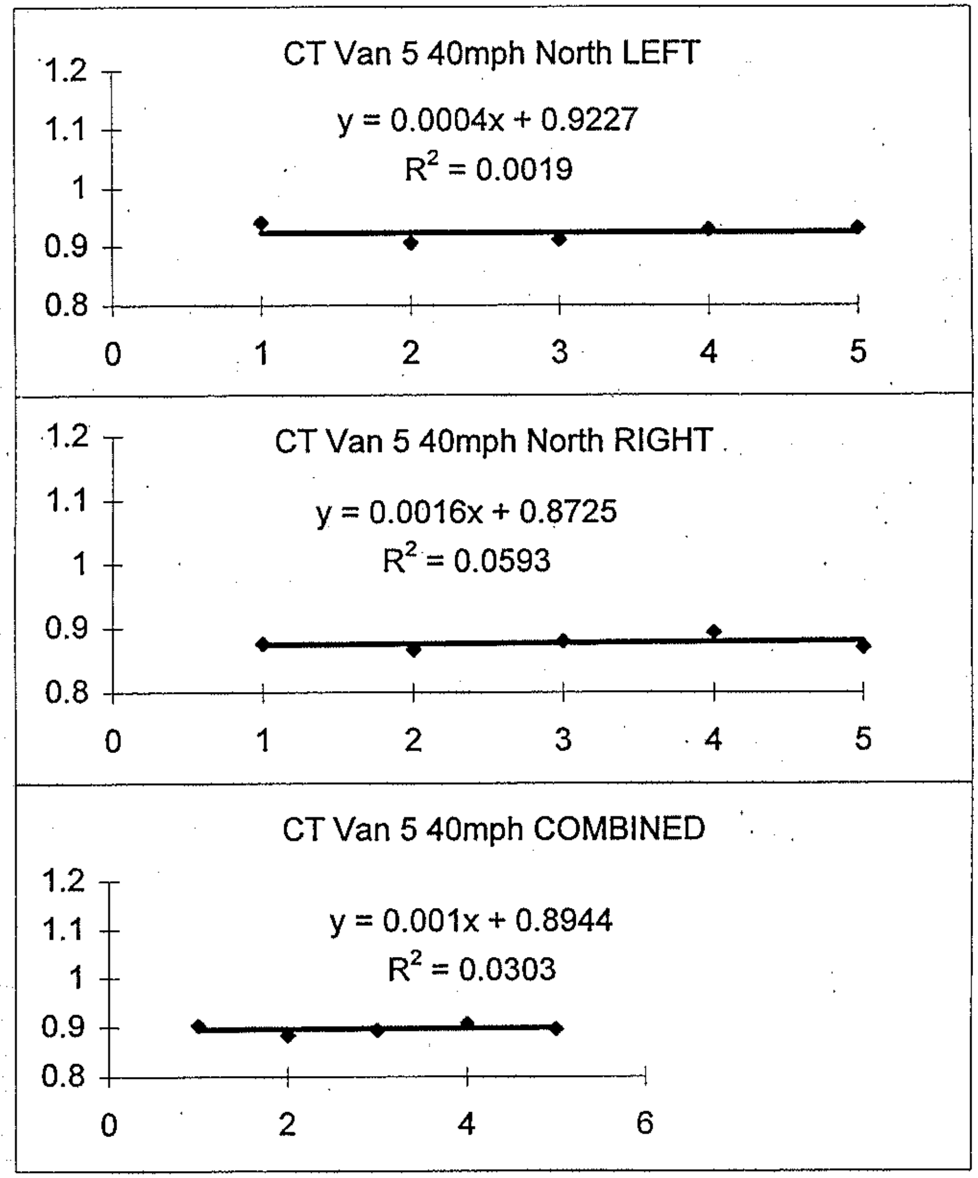
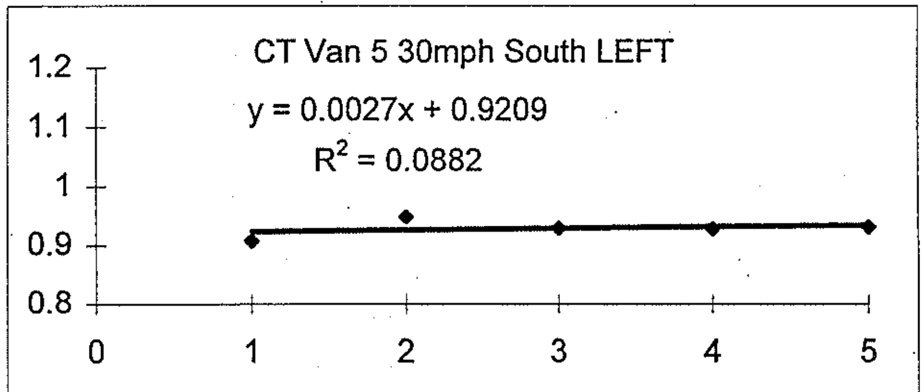
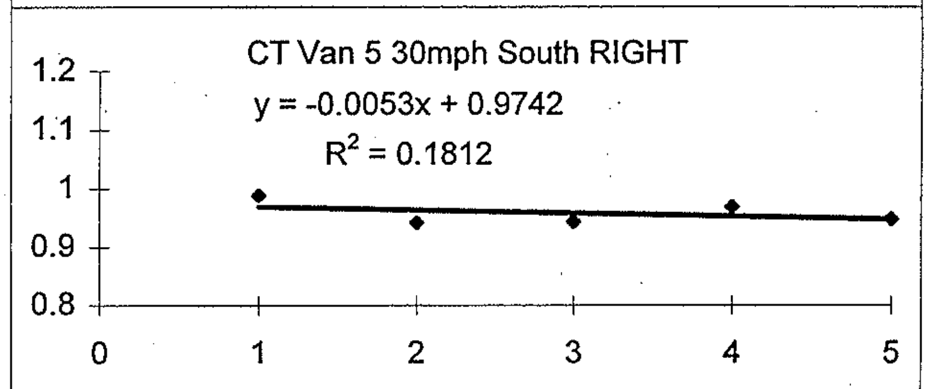


Figure 4.4b The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 North 40mph) IRI

CT VAN 5 ~30mph		
LEFT	Ratio	IRI
1	0.908056	128.39
2	0.948228	134.07
3	0.928991	131.35
4	0.928213	131.24
5	0.931466	131.7
$y = 0.0027x + 0.9209$		
$R^2 = 0.0882$		



CT VAN 5 ~30mph		
RIGHT	Ratio	IRI
1	0.988171	172.93
2	0.942171	164.88
3	0.944114	165.22
4	0.968514	169.49
5	0.948457	165.98
$y = -0.0053x + 0.9742$		
$R^2 = 0.1812$		



CT VAN 5 ~30mph		
COMBINE	Ratio	IRI
1	0.952339	150.66
2	0.94488	149.48
3	0.937295	148.28
4	0.950442	150.36
5	0.940834	148.84
$y = -0.0017x + 0.9504$		
$R^2 = 0.1901$		

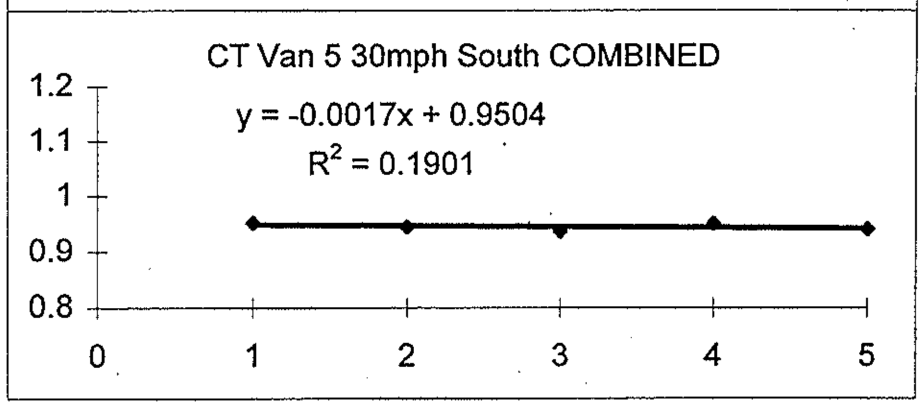
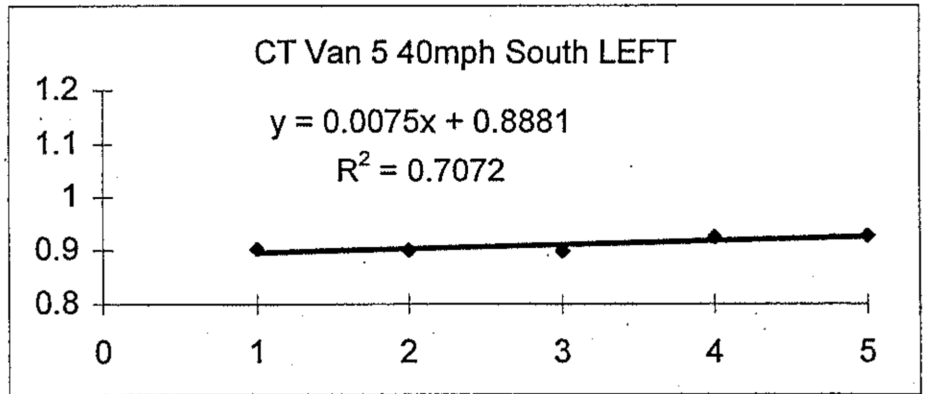
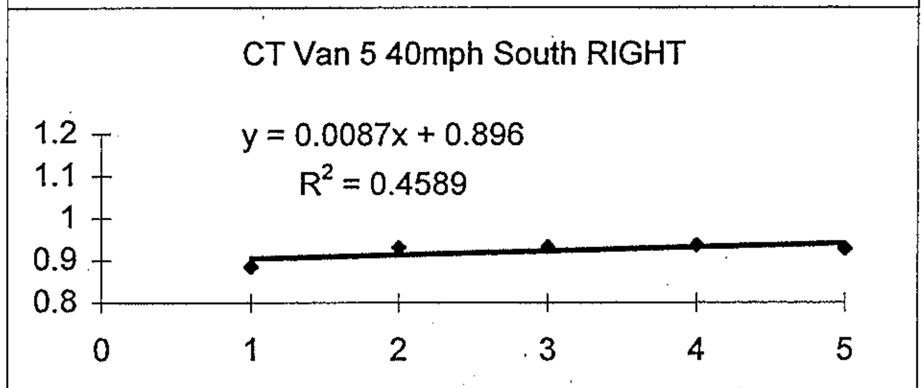


Figure 4.4c The regression Analysis between Dipstick IRI and SHA Device (CT Van 5 South 30mph) IRI

CT VAN 5 ~40mph		
LEFT	Ratio	IRI
1	0.901903	127.52
2	0.900276	127.29
3	0.898791	127.08
4	0.924606	130.73
5	0.927152	131.09
y = 0.0075x + 0.8881		
R^2 = 0.7072		



CT VAN 5 ~40mph		
RIGHT	Ratio	IRI
1	0.886171	155.08
2	0.930229	162.79
3	0.931714	163.05
4	0.935543	163.72
5	0.927086	162.24
y = 0.0087x + 0.896		
R2 = 0.4589		



CT VAN 5 ~40mph		
COMBINE	Ratio	IRI
1	0.893173	141.3
2	0.916814	145.04
3	0.916941	145.06
4	0.930657	147.23
5	0.927118	146.67
y = 0.0082x + 0.8924		
R^2 = 0.7798		

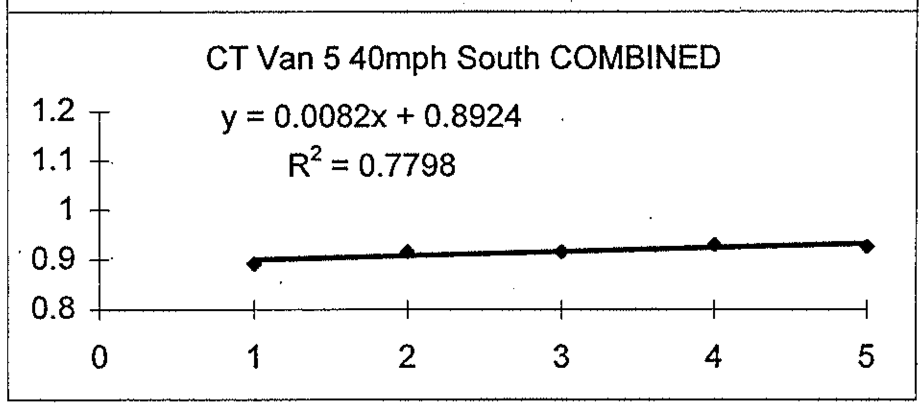
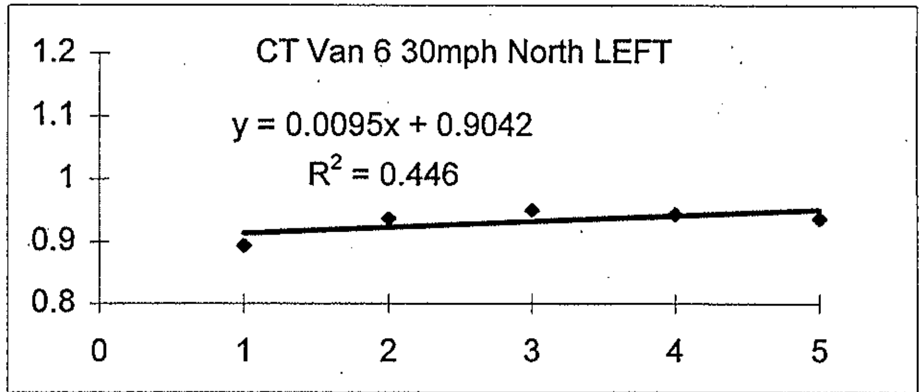
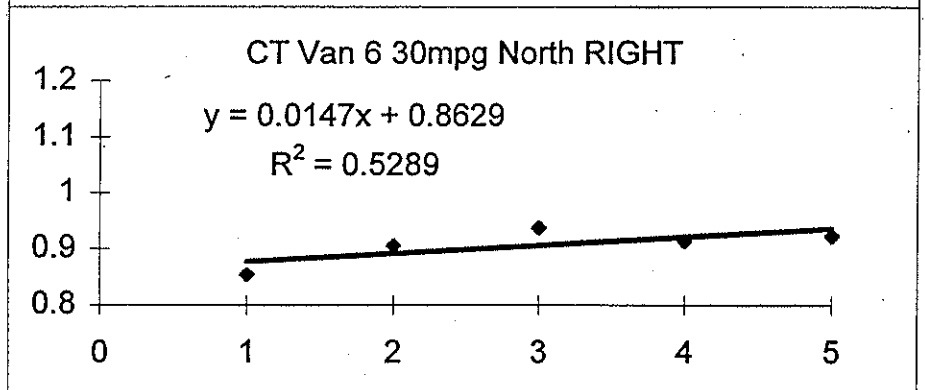


Figure 4.4d The Regression Analysis between Dipstick IRI and SHA Device (CT Van 5 South 40mph) IRI

CT VAN 6 ~30mph		
LEFT	Ratio	IRI
1	0.893794	126.74
2	0.936812	132.84
3	0.950705	134.81
4	0.944429	133.92
5	0.937377	132.92
y = 0.0095x + 0.9042		
R^2 = 0.446		



CT VAN 6 ~30mph		
RIGHT	Ratio	IRI
1	0.853842	156.33
2	0.906003	165.88
3	0.937845	171.71
4	0.91425	167.39
5	0.923316	169.05
y = 0.0147x + 0.8629		
R^2 = 0.5289		



CT VAN 6 ~30mph		
COMBINE	Ratio	IRI
1	0.871283	141.54
2	0.919421	149.36
3	0.943429	153.26
4	0.927424	150.66
5	0.929394	150.98
y = 0.0124x + 0.8809		
R^2 = 0.506		

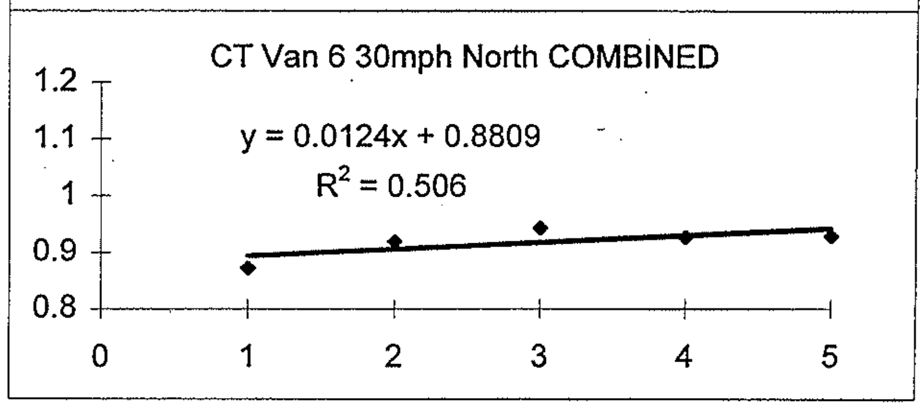


Figure 4.4e The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 North 30mph) IRI

CT VAN 6 ~40mph		
LEFT	Ratio	IRI
1	0.947109	134.3
2	0.92031	130.5
3	0.903949	128.18
4	0.95141	134.91
5	0.912906	129.45
$y = -0.0037x + 0.9383$		
$R^2 = 0.0784$		

CT VAN 6 ~40mph		
RIGHT	Ratio	IRI
1	0.882681	161.61
2	0.874488	160.11
3	0.890327	163.01
4	0.902671	165.27
5	0.892184	163.35
$y = 0.0047x + 0.8743$		
$R^2 = 0.4972$		

CT VAN 6 ~40mph		
COMBINE	Ratio	IRI
1	0.90631	147.23
2	0.894491	145.31
3	0.896214	145.59
4	0.923915	150.09
5	0.9012	146.4
$y = 0.0019x + 0.8987$		
$R^2 = 0.0659$		

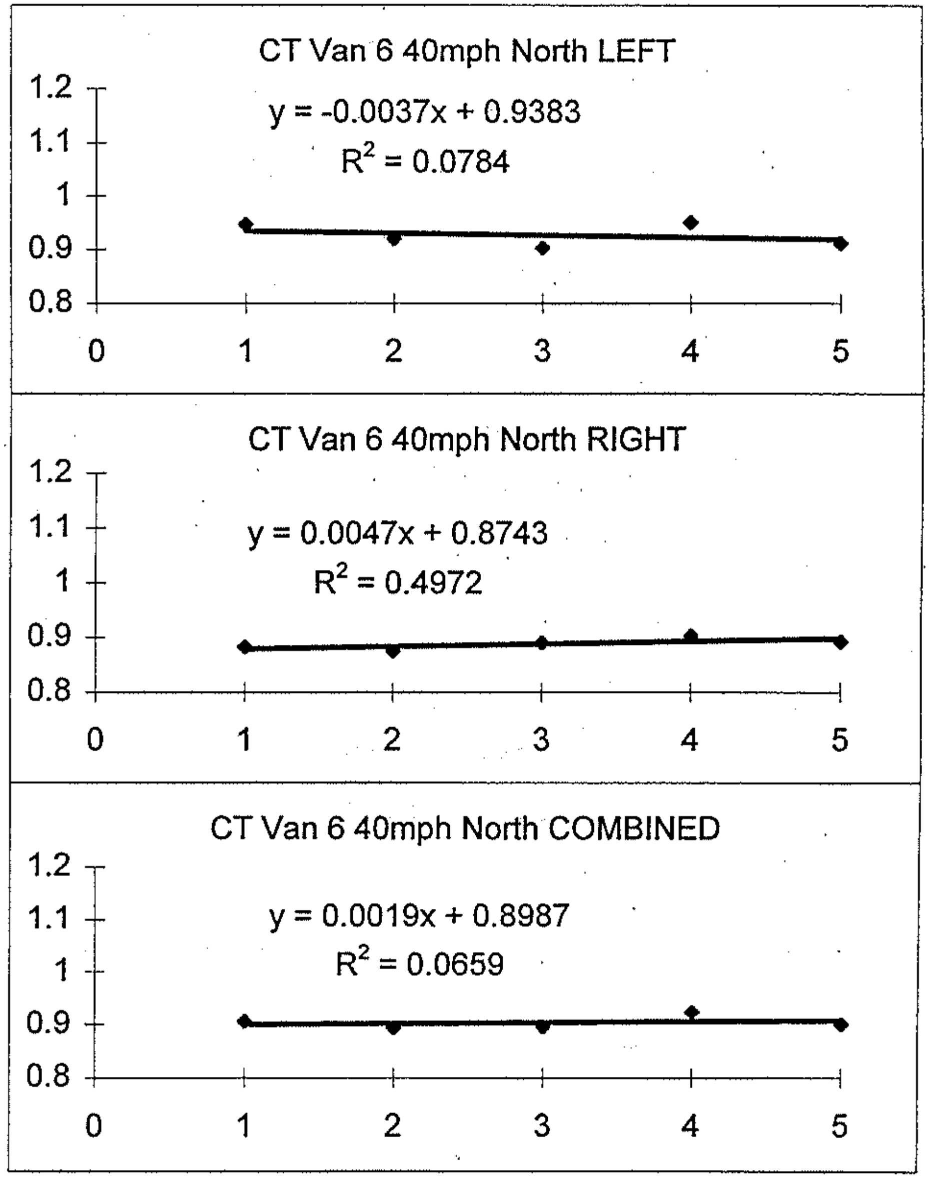
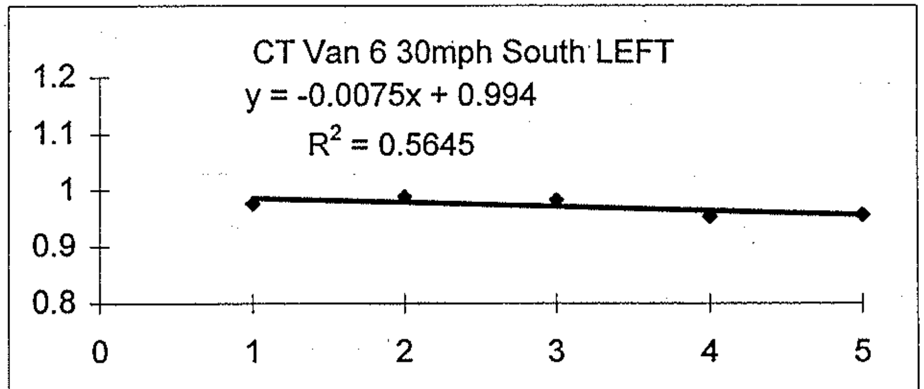
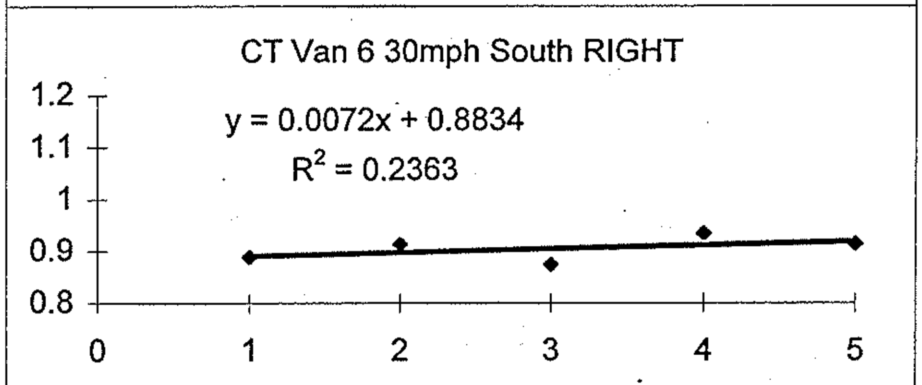


Figure 4.4f The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 North 40mph) IRI

CT VAN 6 ~30mph		
LEFT	Ratio	IRI
1	0.976448	138.06
2	0.988684	139.79
3	0.982601	138.93
4	0.953179	134.77
5	0.956645	135.26
y = -0.0075x + 0.994		
R^2 = 0.5645		



CT VAN 6 ~30mph		
RIGHT	Ratio	IRI
1	0.878971	153.82
2	0.917086	160.49
3	0.912743	159.73
4	0.9544	167.02
5	0.940114	164.52
y = 0.0072x + 0.8834		
R^2 = 0.2363		



CT VAN 6 ~30mph		
COMBINE	Ratio	IRI
1	0.979393	154.94
2	0.949052	150.14
3	0.943932	149.33
4	0.953793	150.89
5	0.947472	149.89
y = -0.0059x + 0.9725		
R^2 = 0.4309		

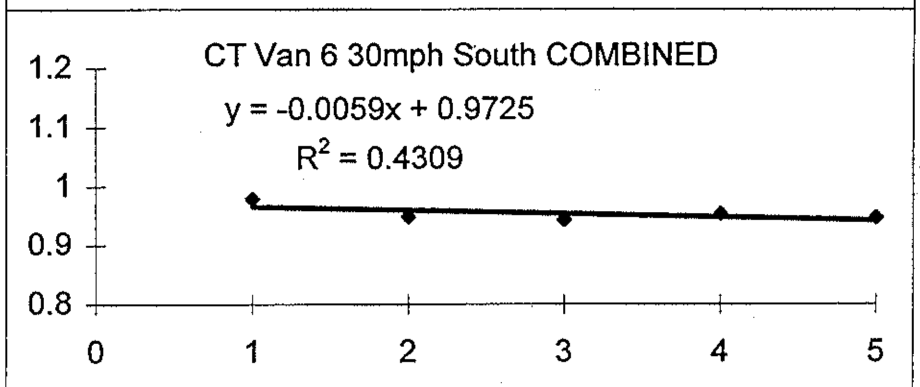
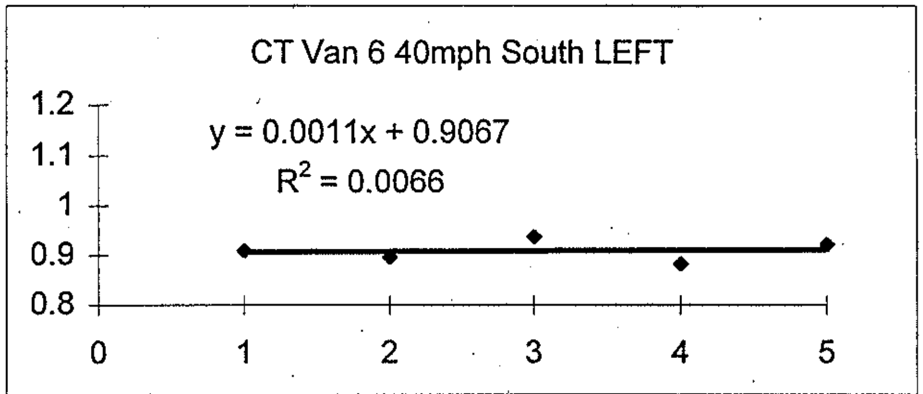
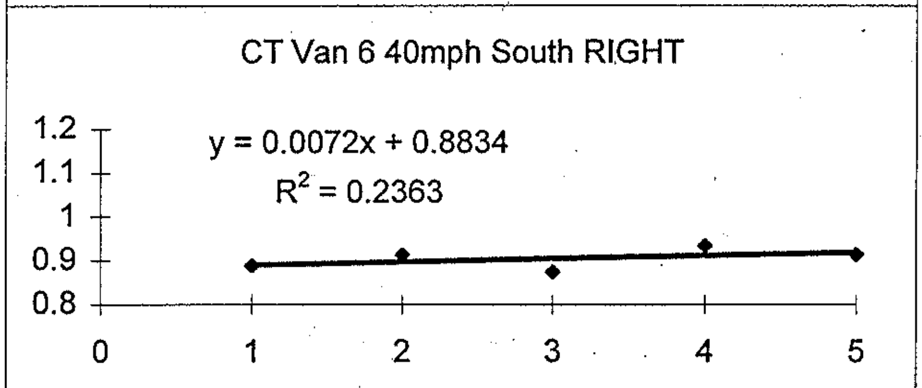


Figure 4.4g The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 South 30mph) IRI

CT VAN 6 ~40mph		
LEFT	Ratio	IRI
1	0.910319	128.71
2	0.896527	126.76
3	0.937336	132.53
4	0.883584	124.93
5	0.922201	130.39
y = 0.0011x + 0.9067		
R^2 = 0.0066		



CT VAN 6 ~40mph		
RIGHT	Ratio	IRI
1	0.888914	155.56
2	0.913257	159.82
3	0.874286	153
4	0.933886	163.43
5	0.914629	160.06
y = 0.0072x + 0.8834		
R^2 = 0.2363		



CT VAN 6 ~40mph		
COMBINE	Ratio	IRI
1	0.89842	142.13
2	0.905752	143.29
3	0.902465	142.77
4	0.911378	144.18
5	0.918015	145.23
y = 0.0045x + 0.8938		
R^2 = 0.851		

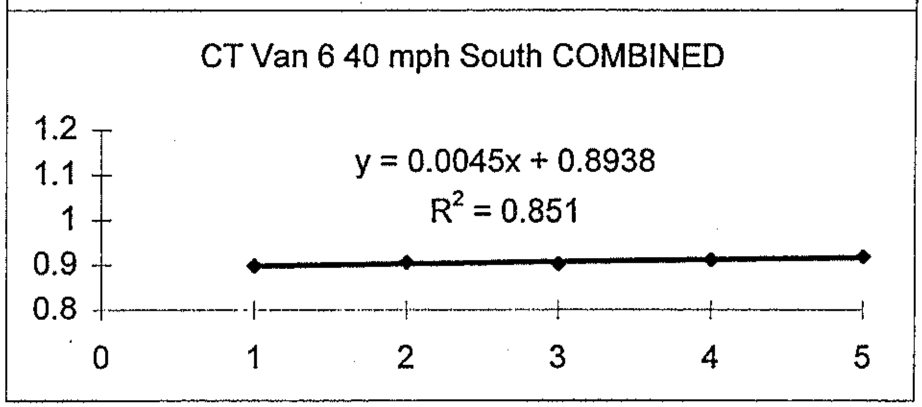


Figure 4.4h The Regression Analysis between Dipstick IRI and SHA Device (CT Van 6 South 40mph) IRI

MA DATA ~40mph		
LEFT	Ratio	IRI
1	0.916714	129.99
2	0.930748	131.98
3	0.943512	133.79
4	0.905712	128.43
5	0.926305	131.35
y = -0.0006x + 0.9264		
R^2 = 0.0042		

MA DATA ~40mph		
RIGHT	Ratio	IRI
1	0.912557	167.08
2	0.906385	165.95
3	0.919712	168.39
4	0.906931	166.05
5	0.932492	170.73
y = 0.004x + 0.9035		
R^2 = 0.3464		

MA DATA ~40mph		
COMBINE	Ratio	IRI
1	0.931794	148.535
2	0.952293	148.965
3	0.892952	151.09
4	0.933826	147.24
5	0.934318	151.04
y = -0.0013x + 0.9331		
R^2 = 0.0095		

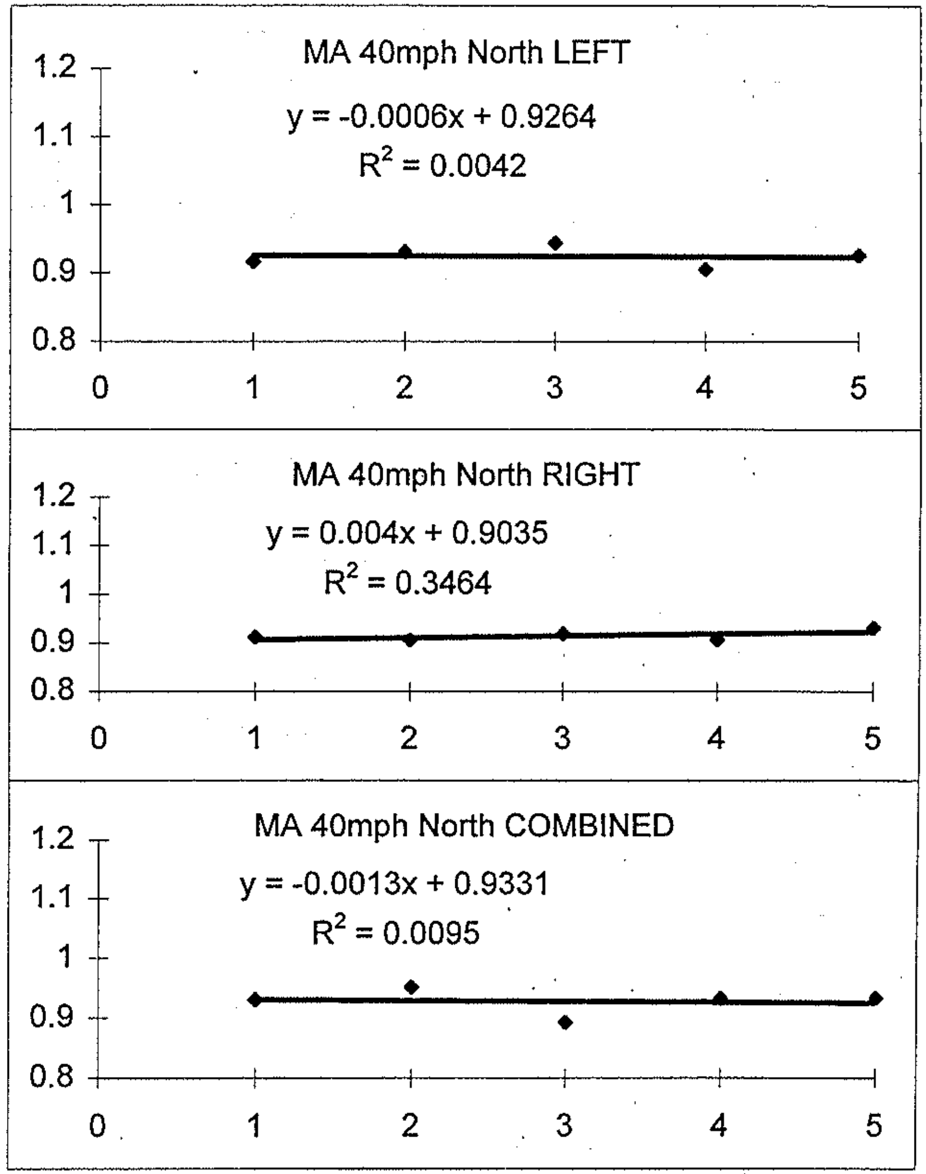


Figure 4.4i The Regression Analysis between Dipstick IRI and SHA Device (MA North 40mph) IRI

MA DATA ~40mph		
LEFT	Ratio	IRI
1	0.975104	137.87
2	0.902539	127.61
3	0.907278	128.28
4	0.921352	130.27
5	0.900134	127.27
y = -0.0131x + 0.9606		
R^2 = 0.4418		

MA DATA ~40mph		
RIGHT	Ratio	IRI
1	0.963543	168.62
2	0.935543	163.72
3	0.9532	166.81
4	0.925886	162.03
5	0.913829	159.92
y = -0.0109x + 0.9711		
R^2 = 0.7347		

MA DATA ~40mph		
COMBINE	Ratio	IRI
1	0.952339	153.245
2	0.94488	145.665
3	0.937295	147.545
4	0.950442	146.15
5	0.940834	143.595
y = -0.0017x + 0.9504		
R^2 = 0.1901		

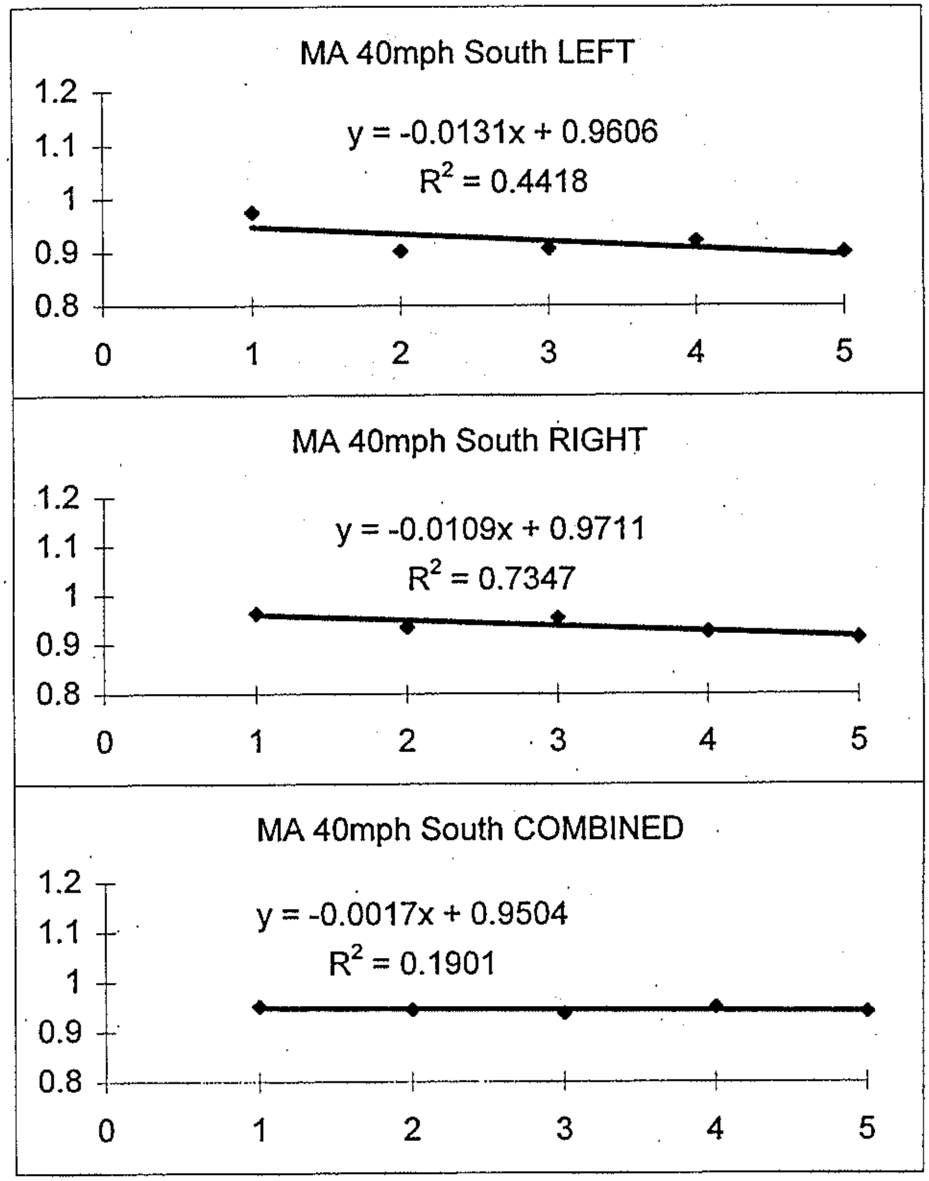
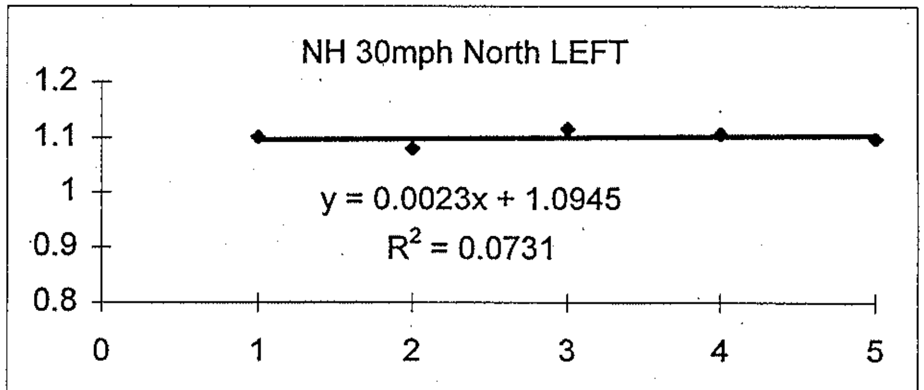
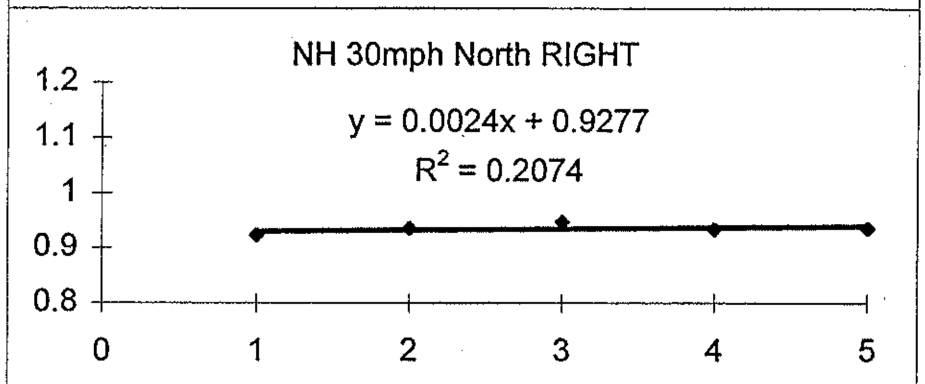


Figure 4.4j The Regression Analysis between Dipstick IRI and SHA Device (MA South 40mph) IRI

NH DATA 30mph North		
LEFT	Ratio	IRI
1	1.101693	156.22
2	1.080818	153.26
3	1.116502	158.32
4	1.10811	157.13
5	1.099365	155.89
$y = 0.0023x + 1.0945$		
$R^2 = 0.0731$		



NH DATA 30mph North		
RIGHT	Ratio	IRI
1	0.923262	169.04
2	0.934895	171.17
3	0.946857	173.36
4	0.934076	171.02
5	0.935715	171.32
$y = 0.0024x + 0.9277$		
R2 = 0.2074		



NH DATA 30mph North		
COMBINE	Ratio	IRI
1	0.931794	162.63
2	0.952293	162.215
3	0.892952	165.84
4	0.933826	164.075
5	0.934318	163.605
$y = -0.0013x + 0.9331$		
$R^2 = 0.0095$		

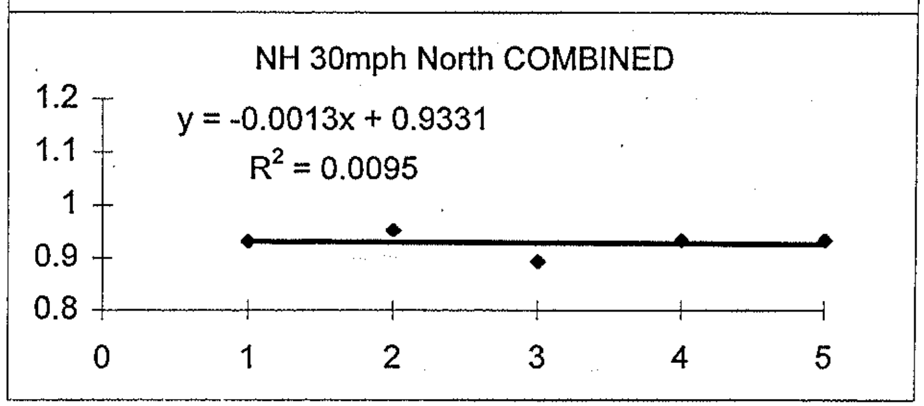


Figure 4.4k The Regression Analysis between Dipstick IRI and SHA Device (NH North 30mph) IRI

NH DATA 40mph North run		
LEFT	Ratio	IRI
1	1.090409	154.62
2	1.064598	150.96
3	1.080677	153.24
4	1.1122	157.71
5	1.096544	155.49
$y = 0.006x + 1.0709$		
$R^2 = 0.2841$		

NH DATA 40mph North run		
RIGHT	Ratio	IRI
1	0.941122	172.31
2	0.939975	172.1
3	0.930253	170.32
4	0.934349	171.07
5	0.920039	168.45
$y = -0.0048x + 0.9475$		
$R^2 = 0.7826$		

NH DATA 40mph North run		
COMBINE	Ratio	IRI
1	0.931794	163.465
2	0.952293	161.53
3	0.892952	161.78
4	0.933826	164.39
5	0.934318	161.97
$y = -0.0013x + 0.9331$		
$R^2 = 0.0095$		

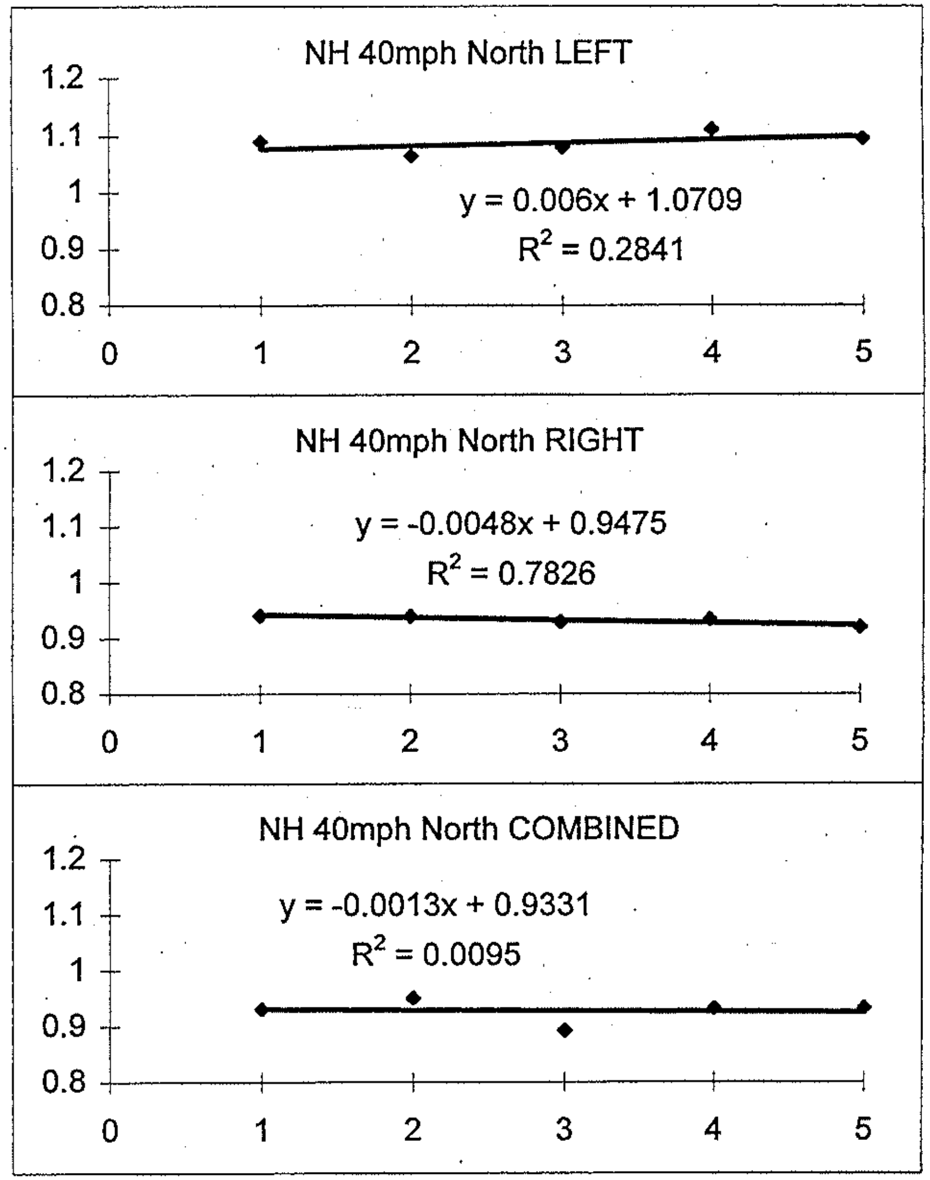


Figure 4.4I The Regression Analysis between Dipstick IRI and SHA Device (NH Nouth 40mph) IRI

NH DATA 30mph South run		
LEFT	Ratio	IRI
1	1.086286	153.59
2	1.087064	153.7
3	1.091661	154.35
4	1.070302	151.33
5	1.084659	153.36
$y = -0.002x + 1.09$		
$R^2 = 0.1533$		

NH DATA 30mph South run		
RIGHT	Ratio	IRI
1	1.082286	189.4
2	1.099829	192.47
3	1.109314	194.13
4	1.098457	192.23
5	1.100914	192.66
$y = 0.0036x + 1.0874$		
$R^2 = 0.3329$		

NH DATA 30mph South run		
COMBINE	Ratio	IRI
1	0.952339	171.495
2	0.94488	173.085
3	0.937295	174.24
4	0.950442	171.78
5	0.940834	173.01
y = -0.0017x + 0.9504		
R2 = 0.1901		

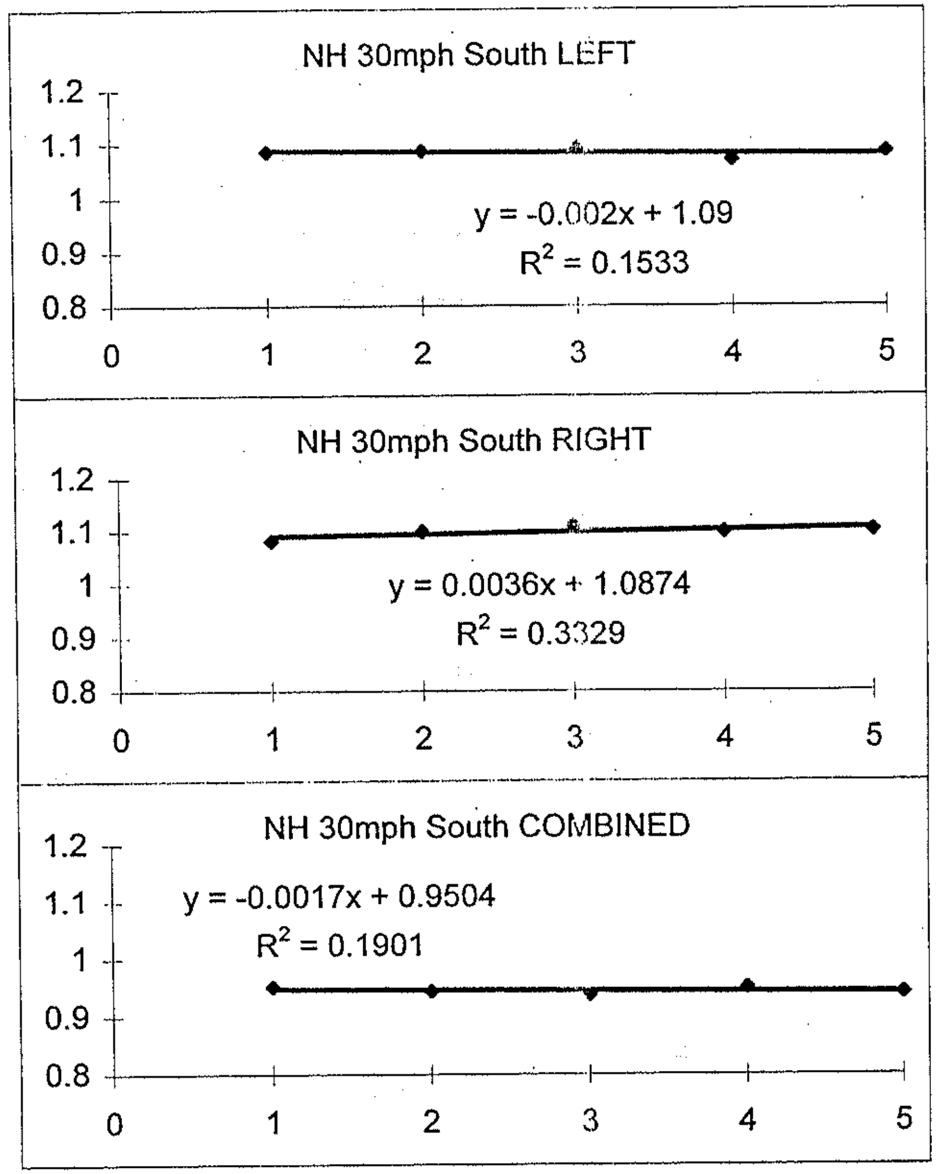


Figure 4.4m The Regression Analysis between Dipstick IRI and SHA Device (NH South 30mph) IRI

NH DATA 40mph South run		
LEFT	Ratio	IRI
1	1.063724	150.4
2	1.083881	153.25
3	1.073485	151.78
4	1.069595	151.23
5	1.104887	156.22
$y = 0.0068x + 1.0587$		
$R^2 = 0.4425$		

NH DATA 40mph South run		
RIGHT	Ratio	IRI
1	1.105429	193.45
2	1.1136	194.88
3	1.096229	191.84
4	1.102743	192.98
5	1.100629	192.61
$y = -0.002x + 1.1099$		
$R^2 = 0.2503$		

NH DATA 40mph South run		
COMBINE	Ratio	IRI
1	0.952339	171.925
2	0.94488	174.065
3	0.937295	171.81
4	0.950442	172.105
5	0.940834	174.415
$y = -0.0017x + 0.9504$		
$R^2 = 0.1901$		

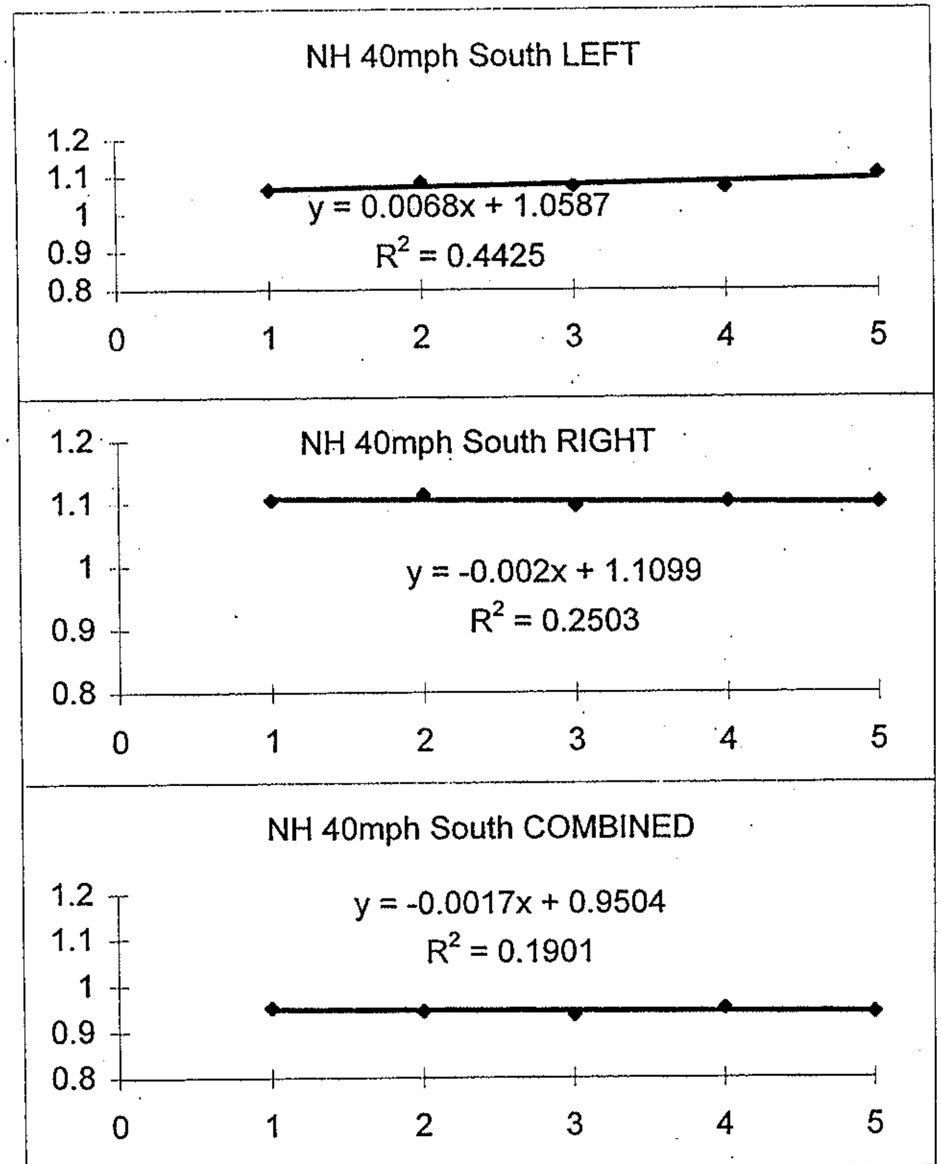
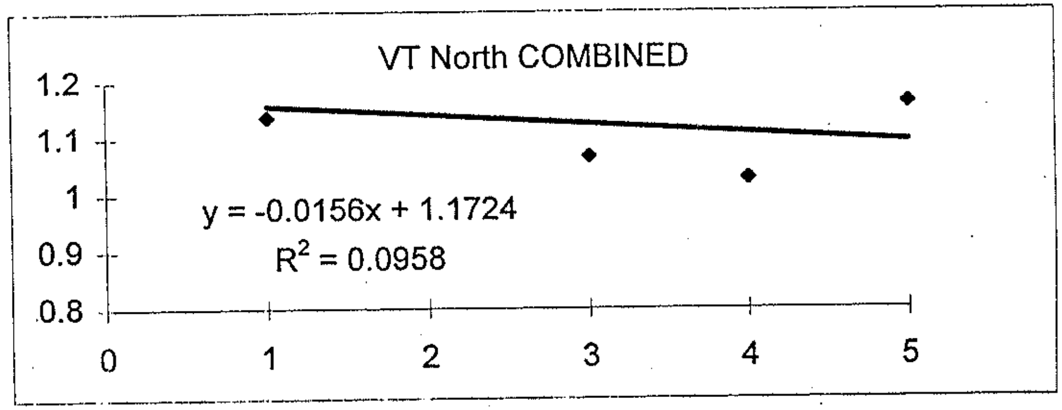


Figure 4.4n The Regression Analysis between Dipstick IRI and SHA Device (NH South 40mph) IRI

VT DATA ~40mph		
COMBINE	Ratio	IRI
1	1.138012	184.87
2	1.231948	200.13
3	1.06759	173.43
4	1.02844	167.07
5	1.161527	188.69
$y = -0.0156x + 1.1724$		
$R^2 = 0.0958$		



VT DATA ~40mph		
COMBINE	Ratio	IRI
1	1.216814	192.5
2	1.273072	201.4
3	1.353477	214.12
4	1.353477	214.12
5	1.257016	198.86
$y = 0.0161x + 1.2425$		
$R^2 = 0.1749$		

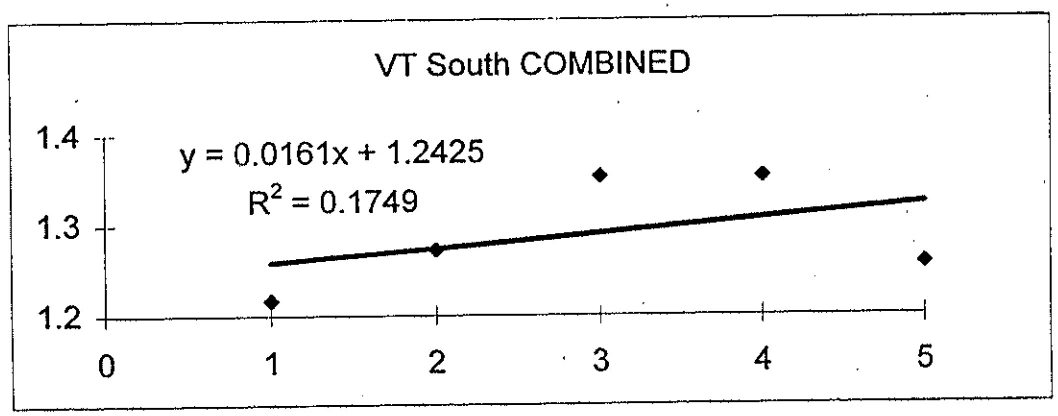


Figure 4.4o The Regression Analysis between Dipstick IRI and SHA Device (VT North and South 40mph) IRI

parameter for comparing various devices when a baseline or reference value can be used to anchor the comparison (as the dipstick IRI values were used in this study). The standard deviation was determined to assess the uniformity of smoothness within individual sublots of each pavement section. The standard deviation within each sublot used in this study appears to be high, indicating a large variation in smoothness within sublots.

Comparison between profiler and dipstick IRI values. In general all ARAN profilers tested had an average IRI lower than the Face Dipstick IRI. In contrast, the average IRI values reported by the New Hampshire K.J. Law profilometer were mostly higher than the dipstick IRI values. Similarly, the Mays Meter IRI values were always higher than the dipstick IRI values.

Comparison of devices. The comparisons among the various devices show a close correlation among all the ARANs, especially for combined average IRI. There appears to be a large difference between the K.J. Law profilometer and ARAN devices. There is also a large difference between the Mays Ride Meter and all other devices. The difference in the combined average IRI values obtained with the dipstick and the values obtained with each inertial profiler is similar, and lies within 10 to 15 in/mi IRI units (0.158 to 0.237 m/km). The difference between the dipstick IRI and the Mays Ride Meter IRI is larger, between 20 and 40 in/mi IRI units (0.316 and 0.631 m/km)

Effect of test speed. The ratios of average IRI at 30 and 40 mph (48.27 and 64.36 km/h) vary between 0% and 7%. Therefore, it appears that the speed effect on the average IRI statistic is very small.

Effect of sensor type. Based on the data presented in Table 4.16, there appears to be a difference in average IRI obtained by the different sensor types, with the optical sensor in New Hampshire's K.J. Law device yielding consistently higher values than the laser sensors in the ARANs. However, neither sensor type appears to be consistently closer to the dipstick IRI values than the other.

Precision and bias . The precision of all profilers (i.e., the repeatability of their results over replicate runs) appears to be excellent, especially for the combined wheel path results. The achieved standard deviations for repeat runs by each device, between 1 and 5 in/mi IRI units (0.016 and 0.079 m/km), are quite low.

The accuracy of the profilers over varied pavement types and speed conditions cannot be stated simply or conclusively. The results presented in Table 4.12 show a wide range of values for each profiler at each site and speed. The average differences between profiler IRIs ad dipstick IRIs presented in Table 4.18 also present a mixed picture. Consequently, no determination of the most accurate device is made by this study.

Regression analysis between dipstick IRI and profiler IRI. The regression analysis conducted in this study shows very little correlation between device IRI and dipstick IRI. A larger database is needed to establish such predictive models.

Table 4.1 CT Data North Site

English Units

DATA Van 5 ~30mph								
Trial	Speed	Std Dev.	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Speed	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	31.3	0.51	134.11	61.72	168.63	72.04	151.37	66.88
2	30.8	0.61	138.10	52.68	171.31	87.68	154.70	70.18
3	31.3	1.14	130.40	51.50	159.71	78.26	145.06	64.88
4	30.4	0.84	138.34	53.56	165.06	85.25	151.70	69.40
5	30.5	0.63	136.69	54.94	166.87	80.13	151.78	67.53
Avg	30.86	0.75	135.53	54.88	166.32	80.67	150.92	67.77
Std Dev			3.32		4.35		3.54	

DATA Van 5 ~40mph								
Trial	Speed	Std Dev.	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Speed	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	41.1	0.74	133.36	62.49	160.37	77.80	146.87	70.15
2	40.6	0.99	128.55	55.73	158.68	77.86	143.62	66.80
3	40.7	0.57	129.32	58.91	161.12	75.60	145.22	67.26
4	41.6	0.69	131.72	59.70	163.52	79.11	147.62	69.41
5	40.7	0.41	132.05	64.58	159.39	79.71	145.72	72.15
Avg	40.9	0.68	131.00	60.28	160.62	78.02	145.81	69.15
Std Dev			2.00		1.87		1.55	

English Units

DATA Van 6 ~30mph								
Trial	Speed	Std Dev.	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Speed	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	30.4	0.92	126.74	66.93	156.33	69.66	141.54	68.30
2	31.0	0.90	132.84	57.73	165.88	74.34	149.36	66.04
3	30.6	0.70	134.81	64.33	171.71	78.13	153.26	71.23
4	31.7	0.80	133.92	59.44	167.39	72.16	150.66	65.80
5	30.3	0.93	132.92	58.77	169.05	73.64	150.98	66.21
Avg	30.9	0.85	132.25	61.44	166.07	73.59	149.16	67.52
Std Dev			3.18		5.86		4.49	

DATA Van 6 ~40mph								
Trial	Speed	Std Dev.	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Speed	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	40.0	0.41	134.30	61.54	161.61	75.23	147.23	68.39
2	40.7	0.78	130.50	63.76	160.11	70.17	145.31	66.96
3	41.0	0.46	128.18	64.93	163.01	70.66	145.59	67.79
4	40.3	0.52	134.91	53.35	165.27	84.07	150.09	68.71
5	39.0	0.36	129.45	56.32	163.35	80.10	146.40	68.21
Avg	40.2	0.51	131.47	59.98	162.67	76.05	146.92	68.01
Std Dev			2.99		1.94		1.92	

NORTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph		in/mile	in/mile		in/mile		
CT VAN 5	30.9	5	135.53	3.32	166.32	4.35	150.92	3.54
	40.9	5	131.00	2	160.62	1.87	145.81	1.55
CT VAN 6	30.9	5	132.25	3.18	166.07	5.86	149.16	4.49
	40.2	5	131.47	2.99	162.67	1.94	146.92	1.92

Table 4.2 CT Data South Site

English Units

DATA Van 5 ~30mph								
Trial	Speed	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Std Dev	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	30.5	0.66	128.39	47.91	172.93	69.95	150.66	58.93
2	30.2	0.95	134.07	47.17	164.88	62.28	149.48	54.72
3	30.2	0.33	131.35	49.55	165.22	66.81	148.28	58.18
4	30.6	1.19	131.24	52.57	169.49	66.97	150.36	59.77
5	30.4	0.41	131.70	50.16	165.98	67.61	148.84	58.88
Avg	30.4	0.71	131.35	49.47	167.70	66.72	149.52	58.10
Std Dev			2.02		3.45		1.00	

DATA Van 5 ~40mph								
Trial	Speed	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Std Dev	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	40.2	0.68	127.52	55.28	155.08	59.27	141.30	57.28
2	40.7	0.30	127.29	53.09	162.79	62.74	145.04	57.92
3	40.6	0.76	127.08	51.76	163.05	63.41	145.06	57.59
4	40.8	0.41	130.73	56.34	163.72	65.63	147.23	60.98
5	40.2	0.71	131.09	53.50	162.24	59.50	146.67	56.50
Avg	40.5	0.57	128.74	53.99	161.38	62.11	145.06	58.05
Std Dev			1.99		3.56		2.32	

DATA Van 6 ~30mph								
Trial	Speed	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Std Dev	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	30.7	0.61	138.06	51.24	153.82	60.06	154.94	55.65
2	30.1	0.46	139.79	51.98	160.49	67.15	150.14	59.56
3	30.3	0.90	138.93	51.86	159.73	63.32	149.33	57.59
4	30.1	0.26	134.77	55.54	167.02	69.82	150.89	62.68
5	30.0	0.37	135.26	50.05	164.52	66.63	149.89	58.34
Avg	30.2	0.52	137.36	52.13	161.12	65.40	151.04	58.76
Std Dev			2.23		5.05		2.25	

DATA Van 6 ~40mph								
Trial	Speed	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Std Dev	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	40.1	0.37	128.71	54.04	155.56	63.85	142.13	58.95
2	39.9	0.25	126.76	50.46	159.82	62.83	143.29	56.65
3	39.2	0.52	132.53	49.81	153.00	62.18	142.77	55.99
4	40.0	0.40	124.93	51.60	163.43	65.66	144.18	58.63
5	39.5	0.69	130.39	48.11	160.06	53.14	145.23	50.62
Avg	39.7	0.45	128.66	50.80	158.37	61.53	143.52	56.17
Std Dev			2.98		4.10		1.22	

SOUTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph		in/mi	in/mile	in/mile	in/mile	in/mile	in/mile
CT VAN 5	30.4	5	131.35	2.02	167.7	3.45	149.52	1.00
	40.5	5	128.74	1.99	161.38	3.56	145.06	2.32
CT VAN 6	30.2	5	137.36	2.23	161.12	5.05	151.04	2.25
	39.7	5	128.66	2.98	158.37	4.1	143.52	1.22

Table 4.3 MA Data North Site

English Units

MA DATA ~40mph								
Trial	Speed	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Std Dev	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	38.9	0.32	129.99	52.65	167.08	64.05	148.54	58.35
2	42.0	0.25	131.98	61.37	165.95	68.38	148.97	64.88
3	41.9	0.23	133.79	57.77	168.39	30.97	151.09	44.37
4	38.1	0.31	128.43	56.79	166.05	61.52	147.24	59.16
5	38.0	0.33	131.35	55.09	170.73	61.72	151.04	58.41
Avg	39.78	0.29	131.11	56.73	167.64	57.33	149.37	57.03
Std Dev			2.03		1.99		1.67	

MA DATA ~30mph								
Trial	Speed	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		Std Dev	IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	33.4	0.46	131.30	51.44	170.49	56.19	150.90	53.82
	33.4	0.46	131.30	51.44	170.49	56.19	150.90	53.82

MA NORTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
MA ARAN	mph		in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
	39.8	5	131.11	2.03	167.64	1.99	149.37	1.67
	33.4	1	131.30	N/A	170.49	N/A	150.90	N/A

Table 4.4 MA Data South Site

English Units

Trial	Speed	Speed Std Dev	Left Wheel Path IRI	Left Wheel Path Std Dev.	Right Wheel Path IRI	Right Wheel Path Std Dev.	Combined Wheel Path IRI	Combined Wheel Path Std Dev.
MA DATA ~40mph								
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	37.5	0.27	137.87	41.54	168.62	52.57	153.25	47.06
2	41.7	0.46	127.61	45.34	163.72	53.18	145.67	49.26
3	39.1	1.55	128.28	40.20	166.81	48.96	147.55	44.58
4	38.6	0.80	130.27	40.95	162.03	48.60	146.15	44.78
5	38.6	0.80	127.27	41.44	159.92	55.06	143.60	48.25
Avg	**39.1**	**0.78**	**130.26**	**41.89**	**164.22**	**51.67**	**147.24**	**46.78**
Std Dev			**4.41**		**3.52**		**3.64**	

Trial	Speed	Speed Std Dev	Left Wheel Path IRI	Left Wheel Path Std Dev.	Right Wheel Path IRI	Right Wheel Path Std Dev.	Combined Wheel Path IRI	Combined Wheel Path Std Dev.
MA DATA ~30mph								
	mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
1	31.2	0.49	138.67	37.22	173.23	56.69	155.95	46.96
Avg	**31.2**	**0.49**	**138.67**	**37.22**	**173.23**	**56.69**	**155.95**	**46.96**

Device	Speed	No. of Trials	Left Wheel Path IRI	Left Wheel Path Std Dev.	Right Wheel Path IRI	Right Wheel Path Std Dev.	Combined Wheel Path IRI	Combined Wheel Path Std Dev.
MA SOUTH SUMMARY								
MA ARAN	mph		in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
	39.1	5	130.26	4.41	164.22	3.52	147.24	3.64
	31.2	1	138.67	N/A	173.23	N/A	155.95	N/A

Table 4.5 NH Data North Site

English Units

NH DATA ~30mph							
Trial	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
(Run No)		IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
(11) 1	~30	156.22	78.26	169.04	71.97	162.63	75.12
(12) 2	~30	153.26	78.43	171.17	78.19	162.22	78.31
3	~30	158.32	86.58	173.36	77.34	165.84	81.96
4	~30	157.13	82.72	171.02	80.58	164.08	81.65
5	~30	155.89	77.40	171.32	76.95	163.61	77.18
Avg	~30	156.16	80.68	171.18	77.01	163.67	78.84
Std Dev		1.88		1.53		1.42	

NH DATA ~40mph							
Trial	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
		IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
6	~40	154.62	72.54	172.31	77.03	163.47	74.79
7	~40	150.96	70.60	172.10	80.38	161.53	75.49
8	~40	153.24	75.64	170.32	76.05	161.78	75.85
9	~40	157.71	83.57	171.07	76.12	164.39	79.85
(16) 10	~40	155.49	85.66	168.45	76.91	161.97	81.29
Avg	~40	154.40	77.60	170.85	77.30	162.63	77.45
Std Dev		2.52		1.56		1.24	

NH NORTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
NH KJLaw	mph		in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
	~30	5	156.16	1.88	171.18	1.53	163.67	1.42
	~40	5	154.40	2.52	170.85	1.56	162.63	1.24

Table 4.6 NH Data South Site

English Units

NH DATA ~30mph							
Trial	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
(Run No)		IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
1	~30	153.59	62.98	189.40	90.38	171.50	76.68
2	~30	153.70	63.29	192.47	92.83	173.09	78.06
3	~30	154.35	60.63	194.13	94.38	174.24	77.51
4	~30	151.33	56.62	192.23	87.56	171.78	72.09
5	~30	153.36	67.14	192.66	103.35	173.01	85.25

Avg	30	153.27	62.13	192.18	93.70	172.72	77.92
Std Dev		1.14		1.72		1.11	

NH DATA 40mph South run							
6	~40	150.40	61.49	193.45	97.92	171.93	79.71
7	~40	153.25	63.18	194.88	99.07	174.07	81.13
8	~40	151.78	58.23	191.84	95.64	171.81	76.94
9	~40	151.23	62.93	192.98	99.13	172.11	81.03
10	~40	156.22	65.29	192.61	95.42	174.42	80.36

Avg	~40	152.58	62.22	193.15	97.44	172.86	79.83
Std Dev		2.29		1.13		1.27	

NH SOUTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
NH KJLaw	mph		in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
	~30	5	153.27	1.14	192.18	1.72	172.72	1.11
	~40	5	152.58	2.29	193.15	1.13	172.86	1.27

Table 4.7 VT Data North Site

English Units

VT DATA ~35 mph	
Trial	Combined Wheel Path
	IRI
	in/mile
1	184.87
2	200.13
3	173.43
4	167.07
5	188.69
Avg	182.84
Std Dev	12.99

VT NORTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
VT Mays Mete	mph		in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
	~35	5	N/A	N/A	N/A	N/A	182.84	12.99

Table 4.8 VT Data South Site

English Units

VT DATA ~35 mph	
Trial	Combined Wheel Path
	IRI
	in/mile
1	192.5
2	201.40
3	214.12
4	214.12
5	198.86

Avg	204.20	42.62
Std Dev	9.62	

VT SOUTH SUMMARY								
Device	Speed	No. of Trials	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
			IRI	Std Dev.	IRI	Std Dev.	IRI	Std Dev.
	mph		in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
	~35	5	N/A	N/A	N/A	N/A	204.2	9.62

Table 4.9 Dipstick Data North and South Sites

English Units

Dipstick North		
Left Wheel Path	Right Wheel Path	Combined Wheel Path
IRI	IRI	IRI
in/mile	in/mile	in/mile
141.80	**183.09**	**162.45**

Dipstick South		
Left Wheel Path	Right Wheel Path	Combined Wheel Path
IRI	IRI	IRI
in/mile	in/mile	in/mile
141.39	**175.00**	**158.20**

Table 4.10 Summary of Results (Metric Units)

Metric Units

Results Summary North									
State Device	No of Runs	Speed	Std Dev	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
				IRI	Std Dev	IRI	Std Dev	IRI	Std Dev
		Km/hr	Km/hr	m/Km	m/Km	m/Km	m/Km	m/Km	m/Km
CT, Van5	5	49.7	1.20	2.14	0.866	2.62	1.273	2.38	1.07
CT, Van5	5	65.9	1.09	2.07	0.969	2.53	1.231	2.30	1.09
CT, Van6	5	49.8	1.37	2.09	0.970	2.62	1.161	2.35	1.06
CT, Van6	5	64.7	0.81	2.07	0.947	2.57	1.200	2.32	1.07
MA	1	53.8	0.74	2.07	0.812	2.69	0.887	2.38	0.85
	5	64.7	0.45	2.07	0.900	2.63	0.89	2.35	0.89
NH	5	~50.0	NA	2.46	1.27	2.70	1.22	2.58	1.24
	5	~64.4	NA	2.39	1.14	2.74	1.289	2.57	1.21
VT	5	NA	NA	NA	NA	NA	NA	2.89	0.67
Dipstick	1	NA	NA	2.24	NA	2.89	NA	2.56	NA

Results Summary South									
State Device	No of Runs	Speed	Std Dev	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
				IRI	Std Dev	IRI	Std Dev	IRI	Std Dev
		Km/hr	Km/hr	m/Km	m/Km	m/Km	m/Km	m/Km	m/Km
CT, Van5	5	48.9	1.14	2.07	0.781	2.65	1.053	2.36	0.92
CT, Van5	5	65.2	0.92	2.03	0.852	2.55	0.980	2.29	0.91
CT, Van6	5	48.7	0.84	2.17	0.823	2.54	1.036	2.36	0.93
CT, Van6	5	64	0.72	2.03	0.801	2.50	0.971	2.26	0.89
MA	1	50.2	0.79	2.19	0.587	2.73	0.895	2.46	0.74
	5	63.1	1.24	2.07	0.660	2.61	0.800	2.34	0.73
NH	5	~50.0	NA	2.42	0.98	3.03	1.48	2.73	1.23
	5	~64.4	NA	2.41	1.03	3.04	1.51	2.75	1.27
VT	5	NA	NA	NA	NA	NA	NA	3.22	0.67
Dipstick	1	NA	NA	2.23	NA	2.76	NA	2.50	NA

Table 4.11 Summary of Results (English Units)

English Units

Results Summary North									
State Device	No of Runs	Speed	Std Dev	Left Wheel Path		Right Wheel Path		Combined Wheel Path	
				IRI	Std Dev	IRI	Std Dev	IRI	Std Dev
		mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
CT, Van5	5	30.9	0.75	135.53	54.88	166.32	80.67	150.92	67.77
CT, Van5	5	40.9	0.68	131.00	60.28	160.62	78.02	145.81	69.15
CT, Van6	5	30.9	0.85	132.25	61.44	166.07	73.59	149.16	67.52
CT, Van6	5	40.2	0.51	131.47	59.98	162.67	76.05	146.92	68.01
MA	1	33.4	0.46	131.30	51.44	170.49	56.19	150.90	53.82
	5	39.8	0.29	131.11	56.73	167.64	57.33	149.37	57.03
NH	5	~30.0	NA	156.16	80.68	171.18	77.01	163.67	78.84
	5	~40.0	NA	151.94	72.22	173.77	81.64	162.85	76.93
VT	5	~35	NA	NA	NA	NA	NA	184.84	42.62
Dipstick	1	NA	NA	141.80	NA	183.09	NA	162.45	NA

Results Summary South									
State Device	No of Runs	Speed	Deviation	Left Path		Right Path		Combined Path	
				IRI	Deviation	IRI	Deviation	IRI	Deviation
		mph	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
CT, Van5	5	30.4	0.71	131.35	49.47	167.70	66.72	149.52	58.10
CT, Van5	5	40.5	0.57	128.74	53.99	161.38	62.11	145.06	58.05
CT, Van6	5	30.2	0.52	137.36	52.13	161.12	65.40	151.04	58.76
CT, Van6	5	39.7	0.45	128.66	50.80	158.37	61.53	143.52	56.17
MA	1	31.2	0.49	138.67	37.22	173.23	56.69	155.95	46.96
	5	39.1	0.78	130.26	41.89	164.22	51.67	147.24	46.78
NH	5	~30.0	NA	153.27	62.13	192.18	93.70	172.72	77.92
	5	~40.0	NA	152.58	62.22	193.15	97.44	172.86	79.83
VT	5	~35	NA	NA	NA	NA	NA		
Dipstick	1	NA	NA	141.39	NA	175.00	NA	158.20	NA

Table 4.12 Effect of Accuracy (Device IRI - Dipstick IRI)

Avg IRI (Device - Dipstick) North Site								
State	Speed	Left Wheel Path		Right Wheel Path		Combined Wheel Path		
Device		Avg IRI	Device-Dipstick	Avg IRI	Device-Dipstick	Avg IRI	Device-Dipstick	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
CT (Van5)	30.9	135.53	-6.27	166.32	-16.77	150.92	-11.53	
	40.9	131.00	-10.80	160.62	-22.47	145.81	-16.64	
CT (VAn6)	30.9	132.25	-9.55	166.07	-17.02	149.16	-13.29	
	40.2	131.47	-10.33	162.67	-20.42	146.92	-15.53	
MA	33.4	131.30	-10.50	170.49	-12.60	150.90	-11.55	
	39.8	131.11	-10.69	167.64	-15.45	149.37	-13.08	
NH	~30.0	156.16	14.36	171.18	-11.91	163.67	1.22	
	~40.0	151.94	10.14	173.77	-9.32	162.85	0.40	
VT	~35.0					182.84	20.39	
Dipstick		141.80		183.09		162.45		

Avg IRI (Device - Dipstick) South Site							
State	Speed	Left Path		Right Path		Combined Path	
Device		Avg IRI	Device-Dipstick	Avg IRI	Device-Dipstick	Avg IRI	Device-Dipstick
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
CT (Van5)	30.4	131.35	-10.04	167.70	-7.30	149.52	-8.68
	40.5	128.74	-12.65	161.38	-13.62	145.06	-13.14
CT (VAn6)	30.2	137.36	-4.03	161.12	-13.88	151.04	-7.16
	39.7	128.66	-12.73	158.37	-16.63	143.52	-14.68
MA	31.2	138.67	-2.72	173.23	-1.77	155.95	-2.25
	39.1	130.26	-11.13	164.22	-10.78	147.24	-10.96
NH	~30.0	153.27	11.88	192.18	17.18	172.72	14.52
	~40.0	152.58	11.19	193.15	18.15	172.86	14.66
VT	~35.0					204.20	46.00
Dipstick		141.39		175.00		158.20	

Table 4.13 Comparison Between Different Devices (Combined Speed, North)

DIFFERENCE AVG IRI,LEFT WHEEL PATH

	CT5	CT6	MA	NH	VT	DIPSTICK
CT5	0.00	-1.40	-2.06	22.02	N/A	8.54
CT6	1.40	0.00	-0.66	23.42	N/A	9.94
MA	2.06	0.66	0.00	24.08	N/A	10.60
NH	-22.02	-23.42	-24.08	0.00	N/A	-13.48
VT	N/A	N/A	N/A	N/A	N/A	N/A
DIPSTICK	-8.54	-9.94	10.60	13.48	N/A	0.00

RIGHT WHEEL PATH

	CT5	CT6	MA	NH	VT	DIPSTICK
CT5	0.00	0.90	5.60	7.54	N/A	19.62
CT6	-0.90	0.00	4.69	6.64	N/A	18.72
MA	-5.60	-4.69	0.00	1.95	N/A	14.03
NH	-7.54	-6.64	-1.95	0.00	N/A	12.08
VT	N/A	N/A	N/A	N/A	N/A	N/A
DIPSTICK	-19.62	-18.72	-14.03	-12.08	N/A	0.00

COMBINED WHEEL PATHS

	CT5	CT6	MA	NH	VT	DIPSTICK
CT5	0.00	-0.33	1.77	14.79	34.48	14.09
CT6	0.33	0.00	2.10	15.11	34.80	14.41
MA	-1.77	-2.10	0.00	13.02	32.71	12.32
NH	-14.79	-15.11	-13.02	0.00	19.69	-0.70
VT	-34.48	-34.80	-32.71	-19.69	0.00	-20.39
DIPSTICK	-14.09	-14.41	-12.32	0.70	20.39	0.00

TABLE 4.14 Comparison Between Different Devices (Combined Speed, South)

DIFFERENCE AVG IRI,LEFT WHEEL PATH

	CT5	CT6	MA	NH	VT	DIPSTICK
CT5	0.00	2.96	4.42	22.88	N/A	11.35
CT6	-2.96	0.00	1.45	19.92	N/A	8.38
MA	-4.42	-1.45	0.00	18.46	N/A	6.93
NH	-22.88	-19.92	-18.46	0.00	N/A	-11.54
VT	N/A	N/A	N/A	N/A	N/A	N/A
DIPSTICK	-11.35	-8.38	-6.93	11.54	N/A	0.00

RIGHT WHEEL PATH

	CT5	CT6	MA	NH	VT	DIPSTICK
CT5	0.00	-4.79	4.19	28.13	N/A	10.46
CT6	4.79	0.00	8.98	32.92	N/A	15.26
MA	-4.19	-8.98	0.00	23.94	N/A	6.28
NH	-28.13	-32.92	-23.94	0.00	N/A	-17.67
VT	N/A	N/A	N/A	N/A	N/A	N/A
DIPSTICK	-10.46	-15.26	-6.28	17.67	N/A	0.00

COMBINED WHEEL PATH

	CT5	CT6	MA	NH	VT	DIPSTICK
CT5	0.00	-0.01	4.30	25.50	56.91	10.91
CT6	0.01	0.00	4.32	25.51	56.92	10.92
MA	-4.30	-4.32	0.00	21.20	52.61	6.60
NH	-25.50	-25.51	-21.20	0.00	31.41	-14.59
VT	-56.91	-56.92	-52.61	-31.41	0.00	-46.00
DIPSTICK	-10.91	-10.92	-6.60	14.59	46.00	0.00

Table 4.15 Speed Effect

RATIO: 30mph/40mph

	NORTH			SOUTH		
	LWP	RWP	COMBINED	LWP	RWP	COMBINED
CT Van 5	1.03	1.04	1.04	1.02	1.04	1.03
CT Van 6	1.01	1.02	1.02	1.07	1.02	1.05
MA	1.00	0.98	0.99	0.94	0.95	0.94
NH	1.01	1.00	1.01	1.00	0.99	1.00
VT	N/A	N/A	N/A	N/A	N/A	N/A
DIPSTICK	N/A	N/A	N/A	N/A	N/A	N/A

Table 4.16 Effect of Different Sensors

	North				South				Combined WP North		Combined WP South	
SENSORS	30 mph		40 mph		30 mph		40 mph		30 mph	40 mph	30 mph	40 mph
	LWP	RWP	LWP	RWP	LWP	RWP	LWP	RWP				
LASER	133.03	167.63	131.19	163.64	135.79	167.35	129.22	161.32	150.33	147.37	152.17	145.27
OPTICAL	156.16	171.18	151.49	173.77	153.27	192.18	152.58	193.15	163.67	162.85	172.72	172.86
MAYS METER									182.84		204.2	
DIPSTICK	141.8	183.09	141.8	183.09	141.39	175.00	141.39	175.00	162.45		158.2	

Table 4.17 (Cont.) Summary of Data-Effect of Repeatability

CT NORTH SUMMARY							
DEVICE	AVG	LEFT WP		RIGHT WP		COMBINED WP		Trials
	SPEED	AVE IRI	STD DEV	AVE IRI	STD DEV	AVE IRI	STD DEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
CT VAN 5	30.9	135.53	3.32	166.32	4.35	150.92	3.54	5
	40.9	131.00	2	160.62	1.87	145.81	1.55	5
CT VAN 6	30.9	132.25	3.18	166.07	5.86	149.16	4.49	5
	40.2	131.47	2.99	162.67	1.94	146.92	1.92	5

CT SOUTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
CT VAN 5	30.4	131.35	2.02	167.7	3.45	149.52	1.00	5
	40.5	128.74	1.99	161.38	3.56	145.06	2.32	5
CT VAN 6	30.2	137.36	2.23	161.12	5.05	151.04	2.25	5
	39.7	128.66	2.98	158.37	4.1	143.52	1.22	5

MA NORTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
MA	39.8	131.11	2.03	167.64	1.99	149.37	1.67	5
MA	33.4	131.30		170.49		150.90		1

MA SOUTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
MA	39.1	130.26	4.41	164.22	3.52	147.24	3.64	5
MA	31.2	138.67		173.23		155.95		1

NH NORTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
NH	~30	156.16	1.88	171.18	1.53	163.67	1.42	5
NH	~40	154.40	2.52	170.85	1.56	162.63	1.24	5

NH SOUTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
NH	~30	153.27	1.14	192.18	1.72	172.72	1.11	5
NH	~40	152.58	2.29	193.15	1.13	172.86	1.27	5

VT NORTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
VT	~35	N/A	N/A	N/A	N/A	182.84	12.99	5

VT SOUTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	
VT	~35	N/A	N/A	N/A	N/A	204.2	9.62	5

DIPSTICK NORTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile		in/mile		in/mile		
DIPSTICK	N/A	141.8	N/A	183.09	N/A	162.45	N/A	1.0

DIPSTICK SOUTH SUMMARY								
DEVICE	AVG	LEFT PATH		RIGHT PATH		COMBINED PATH		Trials
	SPEED	AVE IRI	STDDEV	AVE IRI	STDDEV	AVE IRI	STDDEV	
	mph	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile	in/mile
DIPSTICK	N/A	141.39	N/A	175.00	N/A	158.2	N/A	N/A

Table 4.18 Effect of Accuracy

(PROFILER IRI - DIPSTICK IRI) COMBINED SPEEDS, FOR ALL DEVICES

	NORTH			SOUTH		
	LEFT	RIGHT	COMBINED	LEFT	RIGHT	COMBINED
CT Van 5	-8.54	-19.62	-14.09	-11.35	-10.46	-10.91
CT Van 6	-9.94	-19.72	-14.41	-8.38	-15.26	-10.92
MA	-10.60	-14.03	-12.32	-6.93	-6.28	-6.60
NH	13.48	-12.08	0.70	11.54	17.67	14.59
VT	N/A	N/A	20.39	N/A	N/A	46.00
DIPSTICK	141.80	183.09	162.45	141.39	175.00	158.20

CHAPTER 5

PROJECT SUMMARY AND A PROPOSED RIDE QUALITY SPECIFICATION

An intent of this project is to aid the State Highway Agencies (SHAs) in New England in addressing issues and questions surrounding the development and implementation of a ride quality specification. To this end, a literature synthesis was conducted and documented as required in Tasks 1 and 3 and reported in Chapter 2 and Appendix 8 (Annotated Bibliography). In addition, a survey of current ride quality and paving practices was performed per Tasks 2 and 4 and summarized in Chapter 3; the survey questionnaire used in this survey can be found in Appendix 2, and selected results of these surveys are presented in Appendices 3 and 4. Ride quality parameters, measuring devices, and procedures are examined per Task 5 and 6 and the results are contained in Chapter 4 and Appendix 6 (IRI Computation). Finally, based on the results of Tasks 1 through 6, a ride quality specification is proposed as a guide (per Task 7); this proposed specification is included in Appendix 5 and is briefly discussed below.

5.1 A Proposed Ride Quality Specification

This section briefly describes the four major sections of the proposed ride quality specification in Appendix 5. It should be noted that SHAs should use this specification only as a guideline when implementing a ride quality specification for hot mix asphalt (HMA) pavements. This specification may or may not meet all the needs or expectations of all SHAs.

5.1.1 General

As reflected in the proposed specification in Appendix 5, it is suggested that some of the following items should be included in the general section of a specification:

- the type of surface being measured
- a proposed schedule for data collection
- the type of paving practices used on projects
- the types of projects not subject to the specification
- sections of the project that are to be excluded from the data collection

5.1.2 Equipment

Equipment used should be capable of acquiring data to estimate smoothness measurements with desirable precision and accuracy levels. In general, this equipment includes contact and noncontact devices as defined by FHWA (16). Class I pavement smoothness measuring devices represent the highest standards of accuracy for measuring pavement smoothness and measure in intervals less than or equal to 1.0 foot (0.305 m). Direct profile measurement of a pavement is recorded with a Class II device. Laser and acoustic techniques, which must be in calibration in accordance to the manufacturer's specifications, are included in this classification. Measurements in this category are recorded every 2 feet (0.610 m) or less. This device should also be capable of calculating the IRI or another measurement parameter subject to the approval of the agency implementing the specification.

5.1.3 Indicators of Roughness

SHAs in the US record initial ride quality using different measurement indicators. The international roughness index (IRI) is a measurement that represents the response of a typical passenger vehicle as a result of a road's roughness (11). A value of zero indicates a perfectly smooth pavement surface; greater value indicate rougher surfaces. The IRI is independent of distance traveled; thus, it can be calculated for any length of section. The IRI value is computed from the surface elevation data collected by a smoothness measuring device in each wheel path. Use of the IRI is being considered by all SHAs in New England (with the exception of the NH DOT) and is suggested in the proposed specification.

5.1.4 Payment Adjustment Criteria

Ride quality bonuses and penalties are used by some agencies as incentives and disincentives to encourage contractors to perform high quality work. It is recommended that a bonus and penalty schedule be applied to a ride quality specification. The values used in the proposed specification should be suitable for the New England region. SHAs should adjust the IRI values and bonus and penalty schedule, as deemed necessary.

Since the average IRI value may not sufficiently capture the variation in IRI over the entire length of the group of intervals, it may be decided by some SHAs that a measure of variation (e.g., standard deviation) should be used together with the average IRI as discussed in endnote 8 in the proposed specification. It should be stressed that the IRI values and bonus and penalty schedule that a SHA deems appropriate may vary from state to state, and that the IRI values in the proposed specification are offered only as a starting point, based on the experience of New England SHAs to date and the results of the field study reported in Chapter 4.

APPENDIX 1

SHA Survey Questionnaire

New England Transportation Consortium / Ride Quality Acceptance of Pavements

SHA Survey Questionnaire

1. What pavement practices are used in your state (materials used, construction methods, etc.)?

2. How do you currently measure ride quality or smoothness? (i.e. What equipment do you use and measures do you employ?)

3. What is appropriate level of ride quality for various highway functional classes?

4. Do acceptable (or tolerable) levels vary by pavement type or method of construction?

5. How does an initial ride quality specification enhance the overall quality of a pavement and life of a pavement?

6. Does the use of such specifications lead to increased construction costs or schedules?

7. What are the advantages, disadvantages and limitations of various pieces of equipment and measurement method? Are these equipment and methods equally appropriate for rigid and flexible pavements?

8. How might pavements to contractors be associated with smoothness specifications?

APPENDIX 2

Contact List of Individuals Involved in the Project

PROJECT COMMITTEE MEMBERS:

CONNECTICUT DEPARTMENT OF TRANSPORTATION

Keith Lane
c/o:
C. Dougan
Manager
Research & Materials
Conn DOT
280 West St.
Tel: 860-258-0321
Fax: 860-258-0399

Colleen Kissane
c/o:
C. Dougan
Manager
Research & Materials
Conn DOT
2800 Berlin Turnpike
Tel: 860-594-3255
Fax: 860-594-3175

MAINE DEPARTMENT OF TRANSPORTATION

Wade McClay
MaineDOT
Division 3
PO Box 1208
Bangor, ME 04401
TEL: 207-941-4500
FAX: 207-990-2667

MASSACHUSETTS HIGHWAY DEPARTMENT

Matthew Turo (Chairman)
Pavement Management Engineer
10 Park Plaza
Boston MA, 02116-3973
TEL: 617-973-7266
FAX: 617-973-8035

Mike Ecmecian
936 Elm St.
Concord, MA 01742
TEL: 508-287-6115
FAX: 508-369-5740

NEW HAMPSHIRE DEPARTMENT OF TRANSPORTATION

Glenn Roberts, P.E.
Bureau of Materials and Research
New Hampshire DOT
John O. Morton Building
P.O. Box 483
Concord, NH 03302-0483
TEL: 603-271-1659
FAX: 603-271-1649

PROJECT COMMITTEE MEMBERS:

RHODE ISLAND DEPARTMENT OF TRANSPORTATION

Lee Perkins
Chief Construction Assistant
R.I. DOT
Construction Operations
Room 119
2 Capitol Hill
Providence, RI 02903
TEL: 401-277-2468 x4311
FAX: 401-272-2740

VERMONT AGENCY OF TRANSPORTATION

Duane Stevens
Pavement Management Condition Survey of Transportation
State of Vermont Agency of Transportation
133 State Street
Administration Building
Montpelier, VT 05633-5001
TEL: 802-828-3527
FAX: 802-828-2848

FEDERAL HIGHWAY ADMINISTRATION

Max Grogg
Federal Highway Administration
Region 1
Leo W. O'Brien Federal Building
Room 719
Albany, NY 12207-2398
TEL: 518-431-4224 x223
FAX: 518-431-4208

WORCESTER POLYTECHNIC INSTITUTE

Tahar El-Korchi
Civil and Environmental
Engineering Department
Worcester Polytechnic Institute
Worcester, MA 01608
Email: tek@wpi.wpi.edu
TEL: 508-831-5518
FAX: 508-831-5808

Norman Wittels
Civil and Environmental
Engineering Department
Worcester Polytechnic Institute
Worcester, MA 01608
Email: wittels@cs.wpi.edu
TEL: 508-831-5636
FAX: 617-738-1358

PROJECT COMMITTEE MEMBERS:

UNIVERSITY OF MASSACHUSETTS AT AMHERST

John Collura
Civil and Environmental Engineering Department
214C Marston Hall
University of Massachusetts at Amherst
Amherst, MA 01003
Email: collura@ecs.umass.edu
TEL: 413-545-5404
FAX: 413-545-2840

Ken Black
Civil and Environmental
Engineering Department
214 Marston Hall
University of Massachusetts at Amherst
Amherst, MA 01003
Email: kbblack@ecs.umass.edu
TEL: 413-545-3852
FAX: 413-545-2840

Matthew Chase
Civil and Environmental
Engineering Department
214 Marston Hall
University of Massachusetts at Amherst
Amherst, MA 01003
Email: mchase@student.umass.edu
FAX: 413-545-2840
TEL: 413-545-0349 (school)
413-533-7391 (home)

ADDITIONAL INDIVIDUALS:

BROCK INDUSTRY CONSORTIUM

Ken Williams
1471 Methuen St.
Dracut, MA 01826
TEL: 508-454-9105
FAX: 508-454-9471

NEW ENGLAND TRANSPORTATION

Gerald McCarthy
Transportation Institute
U-202
University of Connecticut
Storrs, CT 06269-5202
TEL: 860- 486- 5400
FAX: 860486- 2399

PIKE INDUSTRY

Jeff Pochily
TEL: 603-286-4324
FAX: 603-286-8102

John Ball
TEL: 1-800-283-7453 x455

THE ASPHALT INSTITUTE

Robert H. Joubert, P.E.
New England District Highway Engineer
101 Amesbury St.
Lawrence, MA 01841
TEL: 508-681-0455

MASSACHUSETTS ASPHALT PAVEMENT ASSOCIATION

Roger MacDonald
TEL: 508-660-1906

MASSACHUSETTS TURNPIKE AUTHORITY

Paul Carr
Deputy Chief
Construction
TEL: 617-237-3250

Bob Lemaitre
Division Engineer
TEL: 617-431-5187

John McQuaid
202 Fuller Road Ext.
Chicopee, MA 01020
TEL: 413- 592- 8014
FAX: 413- 592- 5338

ADDITIONAL INDIVIDUALS:

ERES, CONSULTANTS, INC.

Frank McCullaugh
TEL: 800-424-9818

Lynn D. Evans
505 West University Avenue
Champaign, IL 61820-3915
TEL: 217-356-4500
FAX: 217-356-3088

CONTACTS FOR OTHER SHAS:

COLORADO DOT

Michael F. Wells
Civil Engineer / Project Manager II
Region 4 - Construction
3201 W. Service Road, Unit A
Evans, Colorado 80620
TEL: 970-350-2135
FAX: 970-339-9530

KANSAS DOT

Roy Rissky
TEL#1: 913-296-3461
TEL#2: 913-296-3576

Bill Parcells
Ride Quality
TEL: 913-291-3846

MICHIGAN DOT

1. George Erickson
TEL#1: 517-373-2286
TEL#2: 517-335-2731
2. Ed Winkler
TEL: 517-373-2300

MISSISSIPPI DOT

Joy F. Portera
Asst. Research Engineer
P.O. Box 1850
Jackson, MS 39215-1850
FAX: 601 359-7110

NORTH CAROLINA

Shie-Shin Wu, Ph.D., P.E.
Asst. State Pavement Management
P.O. Box 25201
Raleigh, N.C. 27611
TEL: 919-250 4094

NY DOT

Timothy P. Timbrook, P.E.
Construction Division
Region 6
107 Broadway
Hornell, NY 14843
TEL: 607-324-8481

OKLAHOMA DOT

Lawrence J. Senkowski, P.E.
Asst. Division Engineer
200 N.E. 21st Street
Oklahoma City, OK 73105-3204
TEL: 405-521-2671

TEXAS DOT

Gary Graham
4203 Bull Creek Road, #37
Austin, TX 78732
TEL: 512-467-5926

CONTACTS FOR OTHER SHAS:

WASHINGTON STATE DOT

Robyn L. Moore, P.E.
Field Operations Support Service
Materials Laboratory Mail Stop: 47365
1655 2nd Avenue
Tumwater, WA 98512
TEL: 360-709-5470
FAX: 360-709-5588

CONTACTS FOR RQ MEASURING EQUIPMENT:

AMES PROFILOGRAPH
John Maurer
Box 310
Ames, IO, 50010
TEL: 800- 205-6355
FAX: 515- 432-1656

DYNATEST

209 Bald Street
PO Box 71
Ojai, CA 93023
TEL: 805- 646-2230
FAX: 805- 640-0345

FACE COMPANIES CORP.
Darrell L. Darrow
427 W. 35th Street
Norfolk, VA 23508
TEL: 804- 624-2121
FAX: 804- 624-2128

INTERNATIONAL CYBERNETICS
Robert E. Olenoski, JR.
Sales and Marketing Manager
P.O. Box 17246
Clearwater, FL 34622
TEL: 813- 547- 0696
FAX: 813- 547- 0251

INTERNATIONAL PIPE
McCracken Division
Corey M. Noonan
Computerized Profilograph
P.O. Box 1708
Sioux City, IA 5102 - 1708
TEL: 712- 277-8111
FAX: 712- 277- 1222

JAMES COX & SONS, INC.
Mike Chadd
P.O. Box 674
Colfax, CA 95713
TEL: 917- 346- 8322

KJ LAW
Kenneth Law, P.E.
42300 W. Nine Mile Road
NOVI, MI 48375-4103
TEL: 800- 521-5245
FAX: 810- 347- 3345

Peter Patanzo
Eastern Sales Manager
TEL: 800- 521- 5245

PATHWAY
Rudy Blanco
P.O. Box 721565
Norman, OK 73070
TEL: 405- 366- 7135
FAX: 405- 366- 7425

CONTACTS FOR RQ MEASURING EQUIPMENT:

ROADWARE
Ivan Vander Deen
Sr. VP, Sales and Marketing
147 East River Road
P.O. Box 520
Paris, Ontario N3l 3T6
Canada
TEL: 519-442-2264
FAX: 519-442-3680

SURFACE SYSTEM INC.
Dennis Scott
Director
8131 Upton Ave. S.
Minneapolis, MN 55431
TEL: 800-662-5656

TRIGG INDUSTRIES INTERNATIONAL., INC.
Harry Trigg III
7007 Willoughby Ave.
Los Angeles, CA 90038
TEL: 213-845-9390
FAX: 213-845-9503

311 Fox Hill Road
Hampton, Virgina 23669
TEL: 757-851-3744
FAX: 757-851-6583

YTTERBERG SCIENTIFIC, INC.
1202 Bergen Parkway
Evergreen, Colorado 80439
TEL: 303-674-2290

PROJECT COMMITTEE MEMBERS:

CONNECTICUT DEPARTMENT OF TRANSPORTATION

Keith Lane
c/o:
C. Dougan
Manager
Research & Materials
Conn DOT
280 West St.
Tel: 860-258-0321
Fax: 860-258-0399

Colleen Kissane
c/o:
C. Dougan
Manager
Research & Materials
Conn DOT
2800 Berlin Turnpike
Tel: 860-594-3255
Fax: 860-594-3175

MAINE DEPARTMENT OF TRANSPORTATION

Wade McClay
MaineDOT
Division 3
PO Box 1208
Bangor, ME 04401
TEL: 207-941-4500
FAX: 207-990-2667

MASSACHUSETTS HIGHWAY DEPARTMENT

Matthew Turo (Chairman)
Pavement Management Engineer
10 Park Plaza
Boston MA, 02116-3973
TEL: 617-973-7266
FAX: 617-973-8035

Mike Ecmecian
936 Elm St.
Concord, MA 01742
TEL: 508- 287-6115
FAX: 508-369-5740

NEW HAMPSHIRE DEPARTMENT OF TRANSPORTATION

Glenn Roberts, P.E.
Bureau of Materials and Research
New Hampshire DOT
John O. Morton Building
P.O. Box 483
Concord, NH 03302-0483
TEL: 603-271-1659
FAX: 603-271-1649

PROJECT COMMITTEE MEMBERS:

UNIVERSITY OF MASSACHUSETTS AT AMHERST

John Collura
Civil and Environmental Engineering Department
214C Marston Hall
University of Massachusetts at Amherst
Amherst, MA 01003
Email: collura@ecs.umass.edu
TEL: 413-545-5404
FAX: 413-545-2840

Ken Black
Civil and Environmental
Engineering Department
214 Marston Hall
University of Massachusetts at Amherst
Amherst, MA 01003
Email: kbblack@ecs.umass.edu
TEL: 413-545-3852
FAX: 413-545-2840

Matthew Chase
Civil and Environmental
Engineering Department
214 Marston Hall
University of Massachusetts at Amherst
Amherst, MA 01003
Email: mchase@student.umass.edu
FAX: 413-545-2840
TEL: 413-545-0349 (school)
413-533-7391 (home)

ADDITIONAL INDIVIDUALS:

ERES, CONSULTANTS, INC.
Frank McCullaugh
TEL: 800-424-9818

Lynn D. Evans
505 West University Avenue
Champaign, IL 61820-3915
TEL: 217-356-4500
FAX: 217-356-3088

CONTACTS FOR OTHER SHAS:

WASHINGTON STATE DOT

Robyn L. Moore, P.E.
Field Operations Support Service
Materials Laboratory Mail Stop: 47365
1655 2nd Avenue
Tumwater, WA 98512
TEL: 360-709-5470
FAX: 360-709-5588

CONTACTS FOR RQ MEASURING EQUIPMENT:

ROADWARE
Ivan Vander Deen
Sr. VP, Sales and Marketing
147 East River Road
P.O. Box 520
Paris, Ontario N31 3T6
Canada
TEL: 519- 442- 2264
FAX: 519- 442- 3680

SURFACE SYSTEM INC.
Dennis Scott
Director
8131 Upton Ave. S.
Minneapolis, MN 55431
TEL: 800- 662- 5656

TRIGG INDUSTRIES INTERNATIONAL., INC.
Harry Trigg III
7007 Willoughby Ave.
Los Angeles, CA 90038
TEL: 213- 845- 9390
FAX: 213- 845-9503

311 Fox Hill Road
Hampton, Virgina 23669
TEL: 757- 851- 3744
FAX: 757- 851- 6583

YTTERBERG SCIENTIFIC, INC.
1202 Bergen Parkway
Evergreen, Colorado 80439
TEL: 303- 674- 2290

APPENDIX 3

RQ Specifications Currently Used in New England and Other Selected States

New England

1. Connecticut Department of Transportation
2. Massachusetts Highway Department
3. Massachusetts Turnpike Agency
4. New Hampshire Department of Transportation
5. Vermont Agency of Transportation

Other States

1. Arizona Department of Transportation
2. Kansas Department of Transportation
3. Michigan Department of Transportation
4. Mississippi Department of Transportation
5. Oklahoma Department of Transportation
6. Texas Department of Transportation

RQ Specifications Currently Used in New England

Connecticut Department of Transportation

RQ SPECIFICATION
Connecticut Department of Transportation

Special Provision
Section 4.06

Article 4.06.03 - Construction Methods, Subarticle 10- Surface Test of Pavement, is amended as follows: **After the last paragraph of the subarticle add the following:**

(a) **Pavement Smoothness (Rideability):** The final pavement surface shall be evaluated for smoothness by testing in accordance with Section 4.06 and as stated herein. The provision will apply to projects requiring a minimum of two (2) courses in which the compacted depth of each course is 1-1/2 inches or greater.

Prior to the final course of pavement being placed, the Engineer will furnish the contractor with an average International Roughness Index (IRI) value for the material placed to date. This value will be provided to the contractor, where possible, within 24 hours of the evaluation and will serve as a guide for the contractor in evaluating the level of conformance with the smoothness specification. The Engineer may evaluate and furnish a second IRI value at the request of the contractor.

The IRI value will be the basis for determining any payment adjustment(s) in accordance with Table 1, Schedule of Adjusted Payment of Section 4.06.04- Method of Measurement, subarticle 4.06.04-7 "Adjustment for Rideability."

(1) Evaluation Method - The final pavement surface shall be evaluated for smoothness utilizing a profilometer with computer software capable of outputting IRI values based on quarter-car simulation. An example of such a device would be the South Dakota profile system being used in the "Automatic Road Analyzer (ARAN)". The data collected generates an IRI value, which is a mathematical summary of the longitudinal surface profile of a road in a wheelpath. By assigning a value for each wheel path for each lane tested, the roughness value will enable the engineer to evaluate the ride quality of the pavement surfaces.

Within 30 days of completion of the paving portion of the project, the profilometer system will be utilized to obtain average test results for each thru lane paved. Only hot-mix asphaltic (HMA) pavement placed on the mainline travel lanes, including bridge decks, will be evaluated. Breakdown lanes and ramps will not be evaluated. The testing will be performed within the limits of resurfacing for the project.

Testing will not be done during rain or other weather conditions determined to be inclement by the Engineer. The roadway surface will be free of moisture and other deleterious material which may affect the evaluation.

If the Engineer determines that additional roadway preparation is required, the contractor shall perform such preparation as directed by the Engineer. The contractor shall ensure that the road can be driven safely at the design speed. If requested by the Engineer, the contractor shall sweep the pavement immediately prior to testing. Any work associated with preparing the roadway for the pavement evaluation will not be measured for payment.

An IRI value for each lane in <u>each</u> direction of travel will be calculated by averaging the data collected for both the left and right wheel paths. These lane values will then be averaged to established a final IRI number representing the roughness value for the roadway in that direction. Separate IRI values will be assigned to each direction of travel.

The IRI values will be used to determine the adjustment(s) in payment(s) to the contractor.

Article 4.06.04 - Method of Measurement:

Add the following subarticle:

7–Adjustment for Rideability: Any adjustment will be applied to the total quantity of HMA Class 1 used for the surface course inclusive of shoulders and breakdown lanes, complete-in-place, conforming to the requirements of Section 4.06 and this provision. The adjustment will be computed based on the following:

The average IRI value for the roadway in a given direction, see Table 1, will determine the percent payment to be applied and the adjustment, if any, the contractor will receive. <u>There will be no negative adjustment (penalty) in payment assessed at this time for IRI numbers greater than 90.</u>

TABLE 1
SCHEDULE FOR PAYMENT

IRI VALUE (INCHES/MILE)	PERCENT ADJUSTMENT
< 50	110
50 - 75	105
76 - 90	100
> 90	Penalty

Note: All values shall be rounded to the nearest whole number. (For example, 75.5 shall be rounded to 76)

Article 4.06.05 - Basis of Payment is amended as follows:

Add the following at the end of the first sentence:

...except as noted herein. An adjustment in payment shall apply to the quantity of HMA Class 1 furnished and placed in accordance with Subarticle 4.06.04-7.

SECTION 460
HOT MIX ASPHALT PAVEMENT

460.20 General.

Hot Mix Asphalt (HMA) previously identified as Class I Bituminous Concrete Pavement Type I-1, shall be composed of one or more of the following: Mineral aggregate, mineral filler if required, bituminous material, and RAP or other specified recycled materials. The pavement shall be constructed in courses as shown on the plans and as directed on the prepared or existing base in accordance with these specifications and in close conformity with the lines, grades, compacted thickness and typical cross section as shown on the plans.

460.21 Composition.

The aggregate fractions shall be sized, graded, and combined in such proportions that the resulting mixture meets the grading requirements of the job mix formula.

Materials

460.40 General

Materials shall meet the requirements in the following subsection of Division III, Materials:

Mineral Aggregate	M3.11.04
Mineral Filler	M3.11.05
Bituminous Materials	M3.11.06

Construction Methods

460.60 General.

Grade control survey shall conform to Subsection 5.07. The Contractor shall furnish, set and maintain all line and grade stakes necessary to guide the automated grade control equipment. Where required these control stakes shall be maintained by the Contractor and used throughout the operations, from the grading of the subbase material up to and including the final layers of the pavement. With the approval of the Engineer and with no increase in cost, a plant may substitute a limited amount (up to 1,000 tons per project) of binder mix for black base. The substitution will be only within the station limits, locations, depths and tonnage as permitted by the Engineer.

Under normal conditions, where more than one course of HMA is to be constructed, the use of the stringline for grade control may be eliminated or discontinued after the construction of the initial layer of HMA. For resurfacing projects, where only one course of HMA is to be

Massachusetts Highway Department

RQ SPECIFICATION
Massachusetts Highway Department

{The following shall be added to "SCOPE OF WORK" in proposal}

QUALITY CONTROL/QUALITY ASSURANCE

The following special provisions are related to Quality Control/Quality Assurance where the Contractor assumes the responsibility for the quality of construction and materials incorporated into the work and will control all the processes leading to the final result. The Contractor will perform all required quality control inspection, sampling, and testing. All material will be considered for acceptance through the Department's quality assurance procedures.

Items designated under the Quality Control/Quality Assurance provisions shall include the following types of Hot Mix Asphalt Pavement:-

Base Course, Binder Course, Dense Binder Course, Top Course, Modified Top Course, Dense Mix, Surface Treatment and Open-Graded Friction Course.

These Hot Mix Asphalt Pavement materials shall be sampled, tested and evaluated for acceptance in accordance with the guidelines specified in these Special Provisions.

All of the following will be required except that pay factors will not be used for final payment. Information will be gathered to serve as a basis for statistical analysis which will be factored into future projects.

SECTION 460
HOT MIX ASPHALT PAVEMENT

{The following entirely replaces Section 460 CLASS I BITUMINOUS CONCRETE PAVEMENT TYPE I-1 and Sections M3.11.03, M3.11.08, and M3.11.09}

{The following shall be added to SECTION 6.00 CONTROL OF MATERIALS}

6.05 Testing by Contractor.

The Contractor shall be responsible for the quality of construction and materials incorporated into the work and will control all the processes leading to the final result. The Contractor will perform all required quality control inspection, sampling, and testing. All material will be considered for acceptance through the Department's quality assurance procedures. The Department has the exclusive right for determining the acceptability of all material incorporated into Department projects. The Department may elect to use the results of the Contractor's inspection, sampling and testing as part of the acceptance procedures. The Contractor shall have an approved control plan and the process/quality control test results will be verified by the Department. In all cases, the Department's testing will be separate from the Contractor's testing and both will be conducted by certified technicians. The Department's test results for quality assurance will be binding and final.

constructed, the use of the stringline for grade control may be eliminated. The use of approved automation may then be substituted for the stringline where lines and grades are found to be satisfactory by the Engineer.

Prior to placing of any HMA, a pre-paving conference shall be held to discuss and approve the paving schedule, source of HMA, type and amount of equipment to be used, sequence of paving pattern, rate of HMA supply, all sampling & testing procedures required, traffic control and general continuity of the operation. Special attention shall be made to the paving pattern sequence to minimize transverse and longitudinal joints, employing tandem paving operations, long pulls and, (subject to approval) Wedge joints. The field supervisors of the above mentioned operations shall attend this meeting. All equipment used shall be approved on the project site prior to starting up each day.

460.61 Transportation and Delivery of Hot Mix Asphalt.

The HMA shall be transported from the plant to the work in vehicles previously cleaned of all foreign materials. During transportation of the HMA from the plant to the spreader at the site, each load shall be fully covered at all times, without exception, with canvas or other suitable material of sufficient size and thickness to furnish complete protection. The HMA shall not be transported such a distance that segregation of the ingredients takes place or that any crust is formed on the surface, bottom or sides of HMA which will not crumble or flatten out when the HMA is dumped or shall otherwise be deleterious to the HMA in place on the roadway.

The vehicles for transporting HMA shall be tight and inside of the bodies shall be evenly and lightly coated with an approved solution, but no excess of lubricant shall be allowed to accumulate in low spots in the body.

When necessary, proper insulation of the vehicles transporting the HMA shall be made to insure that the HMA is delivered for placing at the proper temperature.

The dispatching of trucks from the plant shall be so arranged that all material which is to be delivered at or on the road surface during any day may be placed and shall have received final compaction before nightfall of the same day, unless artificial light, satisfactory to the Engineer is provided. During paving operations, the contractor shall provide for ongoing two-way radio or cellular phone communication between the jobs site and the plant.

The temperature of the HMA, within a tolerance of plus or minus 20°F, when delivered at the project site will be governed by the temperature as specified in the contractors approved Plan.

460.62 Tack Coat.

When it is required that the existing hardened surface shall be utilized as a base for the new pavement, a tack coat of bituminous material of the kind and grade shown on the plans shall be uniformly applied by mechanical means to the present surface, at the rate of application of either

Note: Pages 5-25 relate to Massachusetts Highway Specifications. They were not included in the Appendix as they are not relevant to ride quality.

Table 460.9 - Thickness Index Acceptance Limits

	Target	LSL	USL
Thickness Index	0	-1	+1

d. Ride Quality. The finished surface of the pavement shall be uniform in appearance, free from irregularities in contour and shall present a smooth-riding surface.

Ride quality evaluation applies to all bituminous concrete roadways receiving 2.0 inches (50 millimeters) or more in plan thickness of new or recycled pavement.

The contractor shall measure the smoothness of pavement by operating a piece of equipment conforming to ASTM E 950-94 Class I device specifications over the finished surface of the mainline pavement, side roads, auxiliary lanes and ramps.

The following surfaces are specifically excluded from the terms of this provision:

1. Bridge decks unless to be overlaid;
2. Side roads less than one sublot section 0.1 mile (200 meters) in length;
3. Shoulders;
4. Pavement on horizontal curves which have a 500 ft. (150 meters) or less centerline radius of curvature and pavement within the super-elevation transition of such curves;
5. Projects less than one-half mile (800 meters) in length (excluding bridge lengths);
6. Existing roadways that are surfaced with less than 2.0 inches (50 millimeters) of new HMA pavement which is placed in one lift;
7. Projects with posted speeds 40 mph (65 km/hr) or less unless specified in the plans;

Equipment:

The pavement profile shall be determined using a Class I road roughness profile device in accordance with the ASTM E 950-94 specifications such as an inertial lightweight profilometer or other style of device that yields compatible results and has been approved by the Department.

The devices that are capable of achieving testing speeds higher than 10 mph (15 km/hr) should be equipped with a precision accelerometer and a vertical distance sensor such as a laser or infrared sensor and onboard computer that will calculate real time International Roughness Index (IRI), independent of speed, plot the profile of the roadway section and calculate the Ride Number (RN), based on ASTM E 1489-97 specifications. This device should also have the capability to simulate the results of a 10 foot (3 meters) straight edge.

Surface Test:

The ride quality of the HMA pavements will be required on the final surface of the pavement. Pavements having multiple courses will have the ride quality determined for the wearing surface and the pavement course immediately below the wearing surface.

When the final surface is an open-graded friction course, the Contractor will perform test before the open-graded friction course is placed and after if it is deemed necessary.

The Contractor will measure the pavement smoothness of each lane section in both wheel paths [a wheel path is defined as being 3 feet (1 meter) from and parallel to each side of the lane to be measured] within 48 hours after final rolling and before the pavement is open to the traffic. Testing will begin 25 feet (7.5 meters) before the approach joint and end 25 feet (7.5 meters) after the departure joint. Just prior to testing, the Contractor shall be responsible to sweep the pavement and remove of all foreign objects or materials on the pavement surface.

Each lane will be divided into 0.1 mile (200 meters) sublot sections starting at the project limits in the direction of traffic. Partial sections may result at either end of the project or as a result of the interruptions of the continuous pavement surface (i.e. bridge approaches, railroad crossing, cessation of daily pavement operations, etc.). If the production of the last day of the project paving is less than one sublot, it will be grouped with the previous day's production for testing. If less than one sublot is paved, that day's production will be grouped with the next day's production.

A day's production is defined as the placement of a minimum of one sublot section of HMA pavement per day.

Smoothness Evaluation and Corrective Actions:

Each sublot section will be tested by the Contractor and an evaluation report will be provided to the Department. A profile index and an average International Roughness Index (IRI) shall be determined for each sublot section of the finished pavement surface.

All areas within each sublot section having high points (bumps) with deviations in excess of 0.3 inches (7.5 millimeters) in a length of 25 feet (7.5 meters) horizontally shall be corrected by the Contractor at his own expense regardless of the average IRI for the entire section.

Pavement surfaces having an initial International Roughness Index (IRI) of more than 120 in/mile (1.9 mm/m) per section shall be corrected to reduce the IRI to 90 in/mile (1.4 mm/m) or less.

When profile corrections are required, the Contractor shall use one or more of the following corrective methods:

a. Removing and replacing the entire pavement thickness;
b. Diamond grinding or use of other profiling devices;
c. Overlaying (not patching) with the specified surface course;
d. Removing the surface by milling and applying a lift(s) of the specified course;
e. Use of other methods that will provide the desired results;

The corrective method(s) chosen by the Contractor shall be subject to the approval of the Department and shall be performed at the Contractor's expense.

The contractor shall retest any sections where corrections were made to verify that the corrections produced an IRI of 90 in/mile (1.4 mm/m) or less per section and provide the Department with the sections profile plot and International Roughness Index for evaluation.

Ride smoothness will be evaluated against the ride smoothness limits in Table 460.10.

Table 460.10 - Ride Smoothness Testing Limits

	Target	LSL	USL
International Roughness Index (IRI)	90	75	95

(8) **Lot Acceptance.** A lot containing non-specification material (less than 1.00 pay factor) may be accepted provided the pay factor is at least 0.75 and there are no isolated defects identified by the Engineer. A lot may be terminated by the Engineer and the material in the shortened lot paid for at a reduced pay factor or the Engineer may order the non-specification material removed.

A lot containing non-specification material that fails to obtain at least a 0.75 pay factor will be rejected. The Contractor may submit a written request for acceptance of the material at a reduced price or approved correction. Such request shall include an engineering analysis showing expected effects on performance. The Engineer will determine whether or not the material may remain in place at the price reduction.

The Engineer may reject material which appears to be defective based on visual inspection. Such rejected material shall not be used in the work.

No payment will be made for the materials rejected by the Engineer unless the Contractor requests the material tested. If so requested prior to disposal, three representative samples will be obtained and tested. The tests results will be statistically evaluated. If found to have a pay factor of less than 0.75 or otherwise specified, no payment will be made and the Contractor will bear the cost of the sampling, testing, and evaluation. If the pay factor is 0.75 or as otherwise specified or greater, payment will be made for the materials at the invoice cost plus 10%.

The work in the lot will be accepted and paid for at a final pay factor when all inspection or test results are completed and evaluated. Before determining the final pay factor, the work may be incorporated into the project provided the current pay factor does not fall below 0.90. If a lot is concluded with fewer than 3 samples, the material will be accepted under **Subsection C - Measured or Tested in Conformance.**

If the current pay factor of a lot falls below 0.90, production shall be terminated. Production may resume after effective actions to improve quality of the production are taken by the Contractor and the actions taken are approved by the Engineer. If it is determined that the resumption of production involves a significant change to the production process, the current lot will be terminated and a new lot begun.

A lot containing an unsatisfactory percentage of non-specification material (less than 1.00 pay factor) is accepted provided the lowest single pay factor has not fallen into the reject portion of Table 460.12.

A lot containing an unsatisfactory percentage of non-specification material with the lowest single pay factor falling into the reject portion of Table 460.12 is rejected. The Contractor shall remove all rejected material from the work.

When approved, it is permissible to voluntarily remove defective material and replace it with new material to avoid or minimize a pay factor of less than 1.00. New material will be sampled, tested, and evaluated for acceptance according to this subsection. Any quantity of material that is determined to be defective may be rejected based on visual inspection or test results. The Contractor shall not incorporate rejected material in the work. The results of tests run on rejected material will be excluded from the lot acceptance tests.

THIS PAGE INTENTIONALLY LEFT BLANK

Table 460.11 Quality Level Analysis by the Standard Deviation Method

PU or PL %*	Upper Quality Index QU or Lower Quality Index QL													
	n = 3	n = 4	n = 5	n = 6	n = 7	n = 8	n = 9	n = 10 to n = 11	n = 12 to n = 14	n = 15 to n = 18	n = 19 to n = 25	n = 26 to n = 37	n = 38 to n = 69	n = 70 to n = 200	n = 201 to n = ∞
100	1.16	1.50	1.79	2.03	2.23	2.39	2.53	2.65	2.83	3.03	3.20	3.38	3.54	3.70	3.83
99		1.47	1.67	1.80	1.89	1.95	2.00	2.04	2.09	2.14	2.18	2.22	2.26	2.29	2.31
98	1.15	1.44	1.60	1.70	1.76	1.81	1.84	1.86	1.91	1.93	1.96	1.99	2.01	2.03	2.05
97		1.41	1.54	1.62	1.67	1.70	1.72	1.74	1.77	1.79	1.81	1.83	1.85	1.86	1.87
96	1.14	1.38	1.49	1.55	1.59	1.61	1.63	1.65	1.67	1.68	1.70	1.71	1.73	1.74	1.75
95		1.35	1.44	1.49	1.52	1.54	1.55	1.56	1.58	1.59	1.61	1.62	1.63	1.63	1.64
94	1.13	1.32	1.39	1.43	1.46	1.47	1.48	1.49	1.50	1.51	1.52	1.53	1.54	1.55	1.55
93		1.29	1.35	1.38	1.40	1.41	1.42	1.43	1.44	1.44	1.45	1.46	1.46	1.47	1.47
92	1.12	1.26	1.31	1.33	1.35	1.36	1.36	1.37	1.37	1.38	1.39	1.39	1.40	1.40	1.40
91	1.11	1.23	1.27	1.29	1.30	1.30	1.31	1.31	1.32	1.32	1.33	1.33	1.33	1.34	1.34
90	1.10	1.20	1.23	1.24	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28	1.28	1.28
89	1.09	1.17	1.19	1.20	1.20	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.22	1.22	1.23
88	1.07	1.14	1.15	1.16	1.16	1.16	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.13	1.13
86	1.04	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
84	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
83	1.00	0.99	0.98	0.97	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.95	0.95	0.95
82	0.97	0.96	0.95	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
81	0.96	0.93	0.91	0.90	0.90	0.89	0.89	0.89	0.89	0.88	0.88	0.88	0.88	0.88	0.88
80	0.93	0.90	0.88	0.87	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84
79	0.91	0.87	0.85	0.84	0.83	0.82	0.82	0.82	0.82	0.81	0.81	0.81	0.81	0.81	0.81
78	0.89	0.84	0.82	0.80	0.80	0.79	0.79	0.79	0.78	0.78	0.78	0.78	0.77	0.77	0.77
77	0.87	0.81	0.78	0.77	0.76	0.76	0.76	0.75	0.75	0.75	0.75	0.74	0.74	0.74	0.74
76	0.84	0.78	0.75	0.74	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.71	0.71	0.71	0.71
75	0.82	0.75	0.72	0.71	0.70	0.70	0.69	0.69	0.69	0.68	0.68	0.68	0.68	0.68	0.67
74	0.79	0.72	0.69	0.68	0.67	0.66	0.66	0.66	0.66	0.65	0.65	0.65	0.65	0.64	0.64
73	0.76	0.69	0.66	0.65	0.64	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.62	0.61	0.61
72	0.74	0.66	0.63	0.62	0.61	0.60	0.60	0.60	0.59	0.59	0.59	0.59	0.59	0.58	0.58
71	0.71	0.63	0.60	0.59	0.58	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.55	0.55
70	0.68	0.60	0.57	0.56	0.55	0.55	0.54	0.54	0.54	0.53	0.53	0.53	0.53	0.53	0.52
69	0.65	0.57	0.54	0.53	0.52	0.52	0.51	0.51	0.51	0.50	0.50	0.50	0.50	0.50	0.50
68	0.62	0.54	0.51	0.50	0.49	0.49	0.48	0.48	0.48	0.48	0.47	0.47	0.47	0.47	0.47
67	0.59	0.51	0.47	0.47	0.46	0.46	0.46	0.45	0.45	0.45	0.45	0.44	0.44	0.44	0.44
66	0.56	0.48	0.45	0.44	0.44	0.43	0.43	0.43	0.42	0.42	0.42	0.42	0.41	0.41	0.41
65	0.52	0.45	0.43	0.41	0.41	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.39	0.39
64	0.49	0.42	0.40	0.39	0.38	0.38	0.37	0.37	0.37	0.37	0.36	0.36	0.36	0.36	0.36
63	0.46	0.39	0.37	0.36	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.33
62	0.43	0.36	0.34	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.31
61	0.39	0.33	0.31	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.28	0.28	0.28	0.28	0.28
60	0.36	0.30	0.28	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25
59	0.32	0.27	0.25	0.25	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.23	0.23
58	0.29	0.24	0.23	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20
57	0.25	0.21	0.20	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
56	0.22	0.18	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15
55	0.18	0.15	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
54	0.14	0.12	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
53	0.11	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
52	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
51	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: For negative values of QU or QL, PU or PL is equal to 100 minus the table value for PU or PL.
If the value of QU or QL does not correspond exactly to a figure in the table, use the next higher figure.
* Within limits for positive values of QU or QL

(9) **Statistical evaluation.** The Standard Deviation Method will be used to determine the percentage of the lot that is outside specification limits.

The number of significant figures used in the calculations will be according to AASHTO R-11, Absolute Method. The estimated percentage of work that is outside of the specification limits for each quality characteristic will be determined as follows:

(a) Determine the arithmetic mean (X) of the test results:

$$X = \frac{\Sigma x}{n}$$

Where: Σ = summation of
x = individual test value of x
n = total number of test values

(b) Calculate the sample standard deviation(s):

$$s = \sqrt{\frac{n\Sigma(x^2) - (\Sigma x)^2}{n(n-1)}}$$

Where: $\Sigma(x^2)$ = summation of the squares of individual test values
$(\Sigma x)^2$ = summation of the individual test values squared

(c) Calculate the upper quality index (Q_U):

$$Q_u = \frac{USL - X}{s}$$

Where: USL: upper specification limit.

Note: The USL is equal to the contract specification limit or the target value plus the allowable deviation.

(d) Calculate the lower quality index (Q_L):

$$Q_L = \frac{X - LSL}{s}$$

Where: LSL = lower specification limit.

Note: The LSL is equal to the contract specification limit or the target value minus the allowable deviation.

(e) From Table 460.11, determine P_U (the estimated percent within the USL). P_U corresponds to a given Q_u. If a USL is not specified, P_U is 100.

(f) From Table 460.11, determine P_L (the estimated percent within the LSL). P_L corresponds to a given Q_L. If a LSL is not specified, P_L is 100.

(g) Determine the Quality Level (total percent within specification limits).

Quality Level = $(P_u + P_L) - 100$

(h) Determine the Pay Factor (PF) for the lot from Table 460.12 using the Quality Level from step 7.

(I) Determine the Composite Pay Factor (CPF) for each lot.

$$CPF = \frac{[f_1(PF_1) + f_2(PF_2) + \ldots + f_j(PF_j)]}{\Sigma f}$$

Where: f_j = price adjustment factor listed in the specifications for the applicable property.

Pf_j = Pay Factor for the applicable property.

Σf = Sum of the "f" (price adjustment) factors.

Table 460.12 Pay Factors
THIS TABLE INTENTIONALLY LEFT BLANK

(10) Composite Pay Factor (CPF). The total price for each lot will be adjusted by a composite pay factor (CPF) based on the properties of gradation, asphalt content, and air voids. Evaluation will be made using the price adjustment factors in Table 460.13 and using the price adjustment (PA) equation.

Table 460.13 - Price Adjustment Factors

PROPERTY		"f" FACTOR
Gradation	#8, #50 and #200 sieves (each)	8
	All other sieves (each)	2
Asphalt Content		40
In-place Air Voids		50

The price adjustment will be determined as follows:

$$PA = (CPF - 1)(Q)(P)(0.40)$$

where:

PA = price adjustment in dollars.
CPF = Composite pay factor with respect to the test properties listed above.
Q = Quantity represented by CPF in tons.
P = Contract unit price per ton.
0.40 = Weight given to the composite price adjustment

Composite price adjustments shall be applied to item 460.74a. Price adjustments may be applied at the end of each month based on all available test results for each lot.

Pavement Thickness. The price adjustment for pavement thickness per lot made of the sum of all sublots, used for calculating the composite pay factor above will be determined as follows:

$$PA = (PF - 1)(Q)(P)(0.20)$$

Where:

PA = Price adjustment payment in dollars.
PF = Pay factor based on statistical analysis on all thickness test results
Q = Quantity represented by all lots on the project.
P = Contract unit price per ton.
0.20 = Weight given to pavement thickness price adjustment.

Price adjustments for pavement thickness shall be applied to item 460.74b. Price adjustments may be applied at the end of each month based on all available test results for each lot.

Ride Smoothness. The price adjustment for ride smoothness per lot will be determined as follows:

$$PA = (PF - 1)(Q)(P)(0.40)$$

Where:

PA = Price adjustment payment in dollars.
PF = Pay factor based on statistical analysis on all sublots.
Q = Quantity of the sum of all lots in tons.
P = Contract unit price per ton.
0.40 = Weight given to quality of ride smoothness price adjustment.

Price adjustments for ride smoothness shall be applied to item 460.74c. Price adjustments may be applied at the end of each month based on all available test results for each lot.

460.76 Inspection at the Plant. Work may be inspected at the point of production. Mixing plants may be inspected for compliance with specified manufacturing methods. Material samples may be obtained for laboratory testing for compliance with quality requirements. The Contractor shall allow full entry by the Engineer at all times to the parts of the plant producing the work.

COMPENSATION

460.80 Method of Measurement

HMA shall be measured by the ton and shall be the actual and verified tonnage, complete in place and approved. The quantity shall be determined only by weight slips that have been properly countersigned by the Engineer at the time of delivery.

Bitumen used for tack, if required by plans or specifications or ordered by the Engineer, will be measured as specified in Subsection 468.80.

The Contractor's Process/Quality Control system as specified in 460.70 will be measured by the ton. Payment will be full compensation for providing and maintaining the approved process/quality control plan and performing all sampling, testing and inspections in conformance with requirements of the contract. Failure of the Contractor to provide properly documented test results in a timely manner will be justification for withholding payments or portions thereof.

Contractor Sampling and Testing for Acceptance as specified in 460.72 will be measured by the ton. The accepted quantity will be paid at the contract pay item shown in the bid schedule. Payment will be full compensation for the work prescribed in this section. Payment for all of this item may be retained, if the Engineer's verification testing invalidates the Contractor testing.

460.81 Basis of Payment

The tonnage of HMA, determined as provided above, will be paid for at the contract unit price per ton of the kind of HMA required, complete in place including butt joint sealant, if required. Bitumen as specified herein to be paid for as tack coat, if required, will be paid for at the contract unit price per gallon under the item for Bitumen for Tack Coat complete in place. Hot Poured Rubberized Asphalt Sealer applied for sealing of longitudinal joints, shall be paid for at the contract unit price per Linear Foot of joint sealed, including all incidentals.

460.82 Payment Items

		Payment Unit
460.01	Hot Mix Asphalt	Ton
460.02	Hot Mix Asphalt, Open Graded	Ton
460.03	Hot Mix Asphalt, Dense ST	Ton
460.04	Hot Mix Asphalt Dense Binder Course for Bridges	Ton
464	Bitumen for Tack Coat	Gallon
464.5	Hot Poured Rubberized Asphalt Sealer	Linear Foot
460.70	Contractor Process/Quality Control	Ton
460.72	Contractor Testing for Acceptance	Ton
999.490	Price Adjustment for Quality of HMA Pavement[1]	Dollar
999.491	Price Adjustment Hot Mix Asphalt Thickness[1]	Dollar
999.492	Price Adjustment for Quality of Ride Smoothness[1]	Dollar

[1] Not a bid item

Massachusetts Turnpike Agency

3. Acceptance. Acceptance of plant-produced materials for stability and air voids will be determined by the Engineer in accordance with the requirements of Subsection B1.35

B. Field-Placed Material. Material placed in the field will be tested for mat density on a lot basis.

1. Mat Density. The lot size will be the same as that indicated in paragraph B1.34 A. One core of finished compacted material shall be taken by the Contractor from each lot. Core locations will be determined by the Engineer on a random basis in accordance with the procedures contained in ASTM D 3665. Cores shall not be taken closer than one foot from a transverse or longitudinal joint or wheel path unless otherwise directed by the Engineer.

2. Sampling. Samples shall be neatly cut within 24 hours of material placement with a core drill or other approved equipment. The minimum diameter of the sample shall be 6 inches. Samples that are clearly defective, as a result of the sampling, shall be discarded and another sample taken. The Contractor and the Engineer shall both determine whether a core is suitable or defective prior to submitting it for testing. The Contractor shall furnish all tools, equipment, labor and materials for cutting samples, cooling the pavement and filling the cored pavement. Cored hole shall be filled in a manner acceptable to the Engineer the same day of the sampling. Cores shall be marked and identified as to number and location.

3. Testing. The bulk specific gravity of each cored sample will be measured by the Authority's quality assurance personnel in accordance with ASTM D 2726 or D 1188, whichever is applicable. The percent compaction (density) of each core will be determined by dividing the bulk specific gravity of each core by the maximum theoretical specific gravity of the core. If necessary, the cores will be trimmed utilizing the plant saw to remove all foreign material.

4. International Roughness Index (IRI). The International Roughness Index (IRI) is applicable to mainline travel lanes only; breakdown lanes, bridges and ramps are excluded. The IRI is a mathematical summary of the longitudinal surface profile of a road in a wheel path. The IRI represents the vibration of a typical passenger vehicle as a result of a road's roughness. The IRI is defined as the ratio of the accumulated suspension motion to the distance travelled (Reference Average Rectified Slope) of a standard quarter-car simulation (one front tire) at the speed of 55 miles per hour. The IRI value for the half-car simulation (two front tires) summarizes the effect of the road's roughness on the front half of a passenger car. The IRI value for Contract testing purposes is the half-car simulation (HCS) IRI and is computed from the surface elevation

data collected by a mechanical profiler for the left and right wheel paths and converted into inches per mile. Please note that 1 meter per kilometer is equal to 63.36 inches per mile. A value of zero is a perfectly smooth pavement surface and values greater indicate rougher surfaces. The IRI is independent of distance travelled; thus it can be calculated for any length of section (i.e. 0.1 mile).

The pavement profile data necessary to calculate the IRI will be collected with a South Dakota Type Profiler equipped with ultrasonic sensors. The following steps will be adhered to for collecting pavement profile data.

a. All data will be referenced by mile from the nearest mile post prior to the newly overlaid section. If the section beginning coincides with a mile post, then all data will be referenced from the mile post one mile prior to the section.

b. Mainline breakdown lanes, bridge decks and ramps will be omitted from the data collection process. Only paving of mainline travel lanes will be tested. Profile testing will be suspended 0.02 of a mile prior to the first and 0.02 of a mile after the last expansion joint on the bridge deck. The exact location for the suspension and resumption will be determined and recorded in the field by the profiler operator. These locations will be used for all test runs in all lanes.

c. Data collection will cease at the nearest mile post after the end of the newly overlaid section.

d. All data will be collected at sampling intervals of normally 1.0 feet along the length of the road in both the left and right wheel paths.

e. All data will be collected at vehicle speeds between 45 and 60 miles per hour, preferably at a uniform speed of 55 mph.

f. The profile data collected in both the left and right wheel path will be evaluated to calculate half-car simulated (HCS) IRI values using the algorithm developed by the World Bank Technical Paper 46.

g. The HCS IRI data will be reported in 0.1 mile intervals, excluding bridge decks.

h. Each pavement lane will be measured twice for the longitudinal pavement profile. If any of the IRI values between the two passes varies outside a tolerance acceptable to the Authority's Quality Assurance

Personnel, then additional testing will be conducted as required.

i. The IRI data for the two acceptable passes will be averaged.

5. Acceptance IRI. Acceptance of field placed material for smoothness at the 10, 50 and 100 percent stage of project completion will be determined by the Engineer at no cost to the Contractor in accordance with the IRI surface profile and payment will be made in accordance with the requirements of Subsection B1.35. The Contractor may at its own expense perform IRI tests for its own quality control.

Retesting of IRI. All costs incurred in retesting will be borne by the Contractor. All retests shall be performed with the South Dakota Type Profiler in strict compliance with the steps outlined above. The Contractor shall notify the Engineer of its intent to retest within five (5) days of receipt of basic data. All tests shall be completed within ten (10) days of notification to the Engineer by the Contractor. Retest data showing reproducability of the original test data within ±5 inches per mile for each lot defined under Subsection B1.35 shall be considered as within tolerance and no adjustment in payment will be made. Retest data outside this tolerance will be considered for adjustment.

6. Acceptance. Acceptance of field-placed material for mat density will be determined by the Engineer in accordance with the requirements of Subsection B1.35.

C. Retesting of Cores. The Contractor may request one retest per lot on field placed material on a random basis within five (5) days of receipt of the test results. Retesting shall be completed within 15 days. The Contractor has the option of monitoring the testing of the sample by the Authority's designated quality assurance laboratory or removing dual samples from the same location. If dual samples are taken, one sample shall be tested by the Authority's quality assurance laboratory and the other shall be tested by an approved, certified commercial laboratory of the Contractor's choice. The original and retest results from the Authority's laboratory shall be averaged for acceptance. All cost associated with retesting shall be borne by the Contractor.

B1.35 Payment Adjustment Criteria

General. Quantities for payment will be adjusted based on the following characteristics of the bituminous mixture and completed pavement.

1. Stability - Payment will be made for each lot (approximately 500 tons) or portion thereof based on the average sta-

bility of the test specimens for the lot. Payment will be as follows:

Stability (lbs)	Percent Payment
1800 (minimum)	100
1700-1799	95
1600-1699	90
1500-1599	75
<1500	0

2. Air Voids - Payment will be made for each lot (approximately 500 tons) or portion thereof based on the average air voids of the test specimens for the lot. Payment will be as follows:

Amount in % that Air Voids Are Outside the Required Limit	Percent Payment
0 - 0.2	100
0.3 - 1.0	95
1.1 - 1.5	85
1.6 - 2.0	50
>2.0	0

3. Compaction - Payment will be made for each lot (approximately 500 tons) or portion thereof based on the compaction of the core specimen for the lot. Payment will be as follows:

Percent Compaction*	Percent Payment
92.0 - 97.0	100
91.5 - 91.9, 97.1 - 97.5	95
90.5 - 91.4, 97.6 - 98.5	85
89.5 - 90.4, 98.6 - 99.5	50
<89.5, >99.5	0

*Compaction is based on the comparison between the core density and the maximum theoretical density of the same core.

4. Pavement Smoothness - Payment will be made for each lot of approximately 500 tons or portion thereof based on the average IRI value for the lot. Payment will be as follows:

IRI Value (inches/mile)	Percent Payment
<50	110
50-75	105
76-90	100
91-100	75
101-120	50
>121	0

5. Any lot resulting in zero payment shall be removed, disposed of and replaced at no additional cost to the Authority. Replacement pavement will be paid for based on the acceptance and payment criteria specified herein.

Payment Example

A lot of 500 tons of Item B1-3, "Bituminous Concrete Pavement (Top Course)," was found to have the following properties:

Stability - 2100 lbs.
Voids - 6.4%
Compaction - 91.8%
Smoothness (IRI) - 73 inches/mile

Stability:	500 tons x 1.0 =	500 tons payment or 0 tons reduction (-)
Voids:	500 tons x 0.95 =	475 tons payment or 25 tons reduction (-)
Compaction:	500 tons x 0.95 =	475 tons payment or 25 tons reduction (-)
Smoothness:	500 tons x 1.05 =	525 tons payment or 25 tons increase (+)

Payment = 500 tons - 0 - 25 - 25 + 25 = 475 tons payment

COMPENSATION

B1.40 Method of Measurement

The quantity of bituminous concrete to be paid for shall be the actual and verified number of tons of bituminous concrete accepted in conformance with Subsection B1.35, complete in place and approved.

The weight slips shall be countersigned on delivery by the Engineer, and any weight slip, not so countersigned, shall be excluded from any payment under the Contract.

The quantity of bituminous material for tack coat except joints will be measured on a square yard basis complete in place.

The quantity of temporary pavement will be measured by the actual and verified number of tons of bituminous concrete, complete in place and accepted. Separate measurement or payment will not

New Hampshire Department of Transportation

Supersedes Spec. Prov.
Dated 3/20/95, & 04/04/95

RQ SPECIFICATION
New Hampshire Department of Transportation

SPECIAL PROVISION

AMENDMENT TO SECTION 106 -- CONTROL OF MATERIALS

Amend the first paragraph of 106.03 by:

Adding "unless otherwise specified in the Special Provisions." to the end of the first sentence, and

Adding "The Contractor shall not rely on the results of Department testing being available for Process Quality Control." after the first sentence.

Amend the third sentence of the second paragraph of 106.03 by:

Inserting "in effect on the" in place of "to" before "date of Invitation for...".

Add the following after the last paragraph of 106.03:

The Contractor may observe the Department's sampling and testing. If a deviation from the specified sampling or testing procedures is observed, the Contractor shall describe the deviation to the Engineer's designated representative immediately and document the deviation in writing within twenty-four (24) hours.

Items designated for acceptance under Quality Assurance (QA) provisions will be randomly sampled and tested in accordance with the recommended acceptance guidelines specified for that item. Acceptance tests will govern in all cases for determination of pay factors without regard to quality control tests.

106.03.1 The Contractor shall provide Process Quality Control adequate to produce work of acceptable quality. The Contractor shall perform process quality control sampling, testing, and inspection during all phases of the work at a rate sufficient to assure that the work conforms to the contract requirements and the minimum guidelines specified for that item.

The Engineer will not sample or test for Process Control or assist in controlling the Contractor's production operations. The Contractor shall provide personnel and testing equipment capable of providing a product which conforms to specified requirements. Continued production of non-conforming work at a reduced price, in lieu of adjustments to bring work into conformance, will not be allowed.

106.03.1.1 The Contractor shall provide and maintain a Process Quality Control Plan, hereinafter referred to as the "Plan", including all the personnel, equipment, supplies, and facilities necessary to obtain samples, perform tests, and otherwise control the quality of the product to meet specified requirements.

The Contractor shall be prepared to present and discuss, at the pre-construction conference, quality control responsibilities for the specific items indicated in the contract. The Contractor shall submit six copies of the Plan to the Engineer for approval, a minimum of ten (10) working days prior to the start of related work. The Contractor shall not start work on the subject items without an approved Plan. Partial payment will not be made for materials subject to specific quality control requirements without an approved Plan. The approval process for the Contractor's Plan may include inspection of testing equipment and a sampling and testing demonstration by the Contractor's technician(s) to assure an acceptable level of performance.

106.03.1.2 All Contractor process quality control testing under the Plan shall be performed by qualified technicians in laboratories approved by the Bureau of Materials and Research. Technician qualifications shall be as described in the specifications for the item being accepted under Quality Assurance provisions.

Laboratory facilities shall be kept clean and all equipment shall be maintained in proper working condition. The Engineer shall be permitted unrestricted access to inspect and review the Contractor's laboratory facility. The Engineer will advise the Contractor in writing of any noted deficiencies concerning the laboratory facility, equipment, supplies, or testing personnel and procedures. Deficiencies shall be grounds for the Engineer to order an immediate stop to incorporating materials into the work until deficiencies are corrected.

106.03.1.3 The Plan shall be administered by a qualified individual. Administrator qualifications shall be described in the specifications for the item being accepted under Quality Assurance provisions.

The individual administering the Plan must be a full-time employee of or a consultant engaged by the Contractor. The individual shall have full authority to institute any and all actions necessary for the successful operation of the Plan.

106.03.1.4 The Plan shall contain a system for sampling that assures all material being produced has an equal chance of being selected for testing. The Engineer shall be provided the opportunity to witness all sampling.

When directed by the Engineer, the Contractor shall sample and test any material which appears inconsistent with similar material being sampled, unless such material is voluntarily removed and replaced or corrected by the Contractor. All sampling shall be in accordance with Department, AASHTO, or ASTM procedures.

106.03.1.5 All testing shall be performed in accordance with the acceptance test procedures applicable to the specified contract items or other methods set forth in the approved Plan. Should acceptance test procedures not be applicable to quality control tests, the Plan shall stipulate the test procedures to be utilized. Upon request the Contractor shall provide copies of all test results on forms meeting the approval of the Engineer.

106.03.1.6 The Contractor shall maintain complete record of all process quality control tests and inspections. The records shall be available to the Engineer for review and copies furnished upon request.

Control Charts acceptable to the Engineer shall be maintained and kept current at a location satisfactory to the Engineer. As a minimum, the Control Charts shall identify the project number, the contract item number, the test number, each test parameter, the upper and lower specification limit applicable to each test parameter and the Contractor's test results. The Contractor shall use the Control Charts as part of a process control system for identifying production and equipment problems and for identifying pay factor reductions before they occur.

106.03.1.7 When a contract pay item for Contractor Process Quality Control is provided, the Contractor will be paid the contract lump sum amount bid according to the following partial payment schedule:

1. Twenty-five percent of the contract lump sum bid amount or one-half percent of the original contract amount, whichever is less, when the quality control plan is approved.
2. The remaining portion of the contract lump sum bid amount will be paid on a prorated basis according to total job progress.

Payment will be full compensation for providing and maintaining the approved quality control plan and performing all sampling, testing, and inspections in conformance with requirements of the contract. Failure of the Contractor to provide properly documented test results in a timely manner will be justification for withholding progress payments or portions thereof.

106.03.2 Items specified to be sampled and tested on a Quality Assurance (QA) basis will be evaluated for acceptance in accordance with the guidelines specified for that item. All acceptance test results for a lot as defined in the specification will be analyzed collectively and statistically by the Quality Level Analysis-Standard Deviation (Specification Conformance Analysis) Method using the procedures listed to determine the total estimated percent of the lot that is within specification limits. Quality Level Analysis (Specification Conformance Analysis) is a statistical procedure for estimating the percent compliance with a specification and is affected by shifts in the arithmetic mean (X) and by the sample standard deviation (s). Analysis of test results will be based on an Acceptable Quality Level (AQL) of 95.0 and a Contractor's risk of 0.05, unless otherwise specified. AQL may be viewed as the lowest percent within the specification limits of a material that is acceptable as a process average and receive 100% pay. The Contractor's risk is the probability that when the Contractor is producing material at exactly the AQL, the materials will receive less than a 1.00 pay factor. Test results on material not incorporated in the work will not be included in the quality level analysis.

106.03.2.1 A lot containing non-specification material (less than 1.00 pay factor) may be accepted provided the pay factor is at least 0.75 and there are no isolated defects identified by the Engineer. A lot may be terminated by the Engineer and the material in the shortened lot paid for at a reduced pay factor or the Engineer may order the non-specification material removed.

106.03.2.2 A lot containing non-specification material that fails to obtain at least a 0.75 pay factor will be rejected. The Contractor may submit a written request for acceptance of the material at a reduced price or approved correction. Such request shall include an engineering analysis showing expected effects on performance. The Engineer will determine whether or not the material may remain in place at the price reduction.

Note: Any lot for which at least three samples have been obtained and which meets the following criteria will receive at least a 1.00 pay factor if:

1. All test results are within the allowable deviations specified for the item, and
2. All test results are greater than or equal to minimum specification limits, or
3. All test results are less than or equal to maximum specification limits, whichever is appropriate.

Computation of the Quality Level in these instances will determine the amount of any quality incentive.

106.03.2.3 The Engineer may reject material which appears to be defective based on visual inspection. Such rejected material shall not be used in the work.

No payment will be made for the materials rejected by the Engineer unless the Contractor requests the material tested. If so requested prior to disposal, three representative samples will be obtained and tested. The tests results will be statistically evaluated. If found to have a pay factor of less than 0.75 or otherwise specified, no payment will be made and the Contractor will bear the cost of the sampling, testing, and evaluation. If the pay factor is 0.75 or as otherwise specified or greater, payment will be made for the materials at the invoice cost plus 10%.

106.03.2.4 Quality Level Analysis - Standard Deviation Method procedures are as follows:

1. Determine the arithmetic mean (X) of the test results:

$$X = \frac{\Sigma x}{n}$$

Where: Σ = summation of
x = individual test value of x
n = total number of test values

2. Compute the sample standard deviation(s):

$$s = \sqrt{\frac{n\Sigma(x^2) - (\Sigma x)^2}{n(n-1)}}$$

Where: $\Sigma(x^2)$ = summation of the square of individual test values.
$(\Sigma x)^2$ = summation of the individual test values squared.

3. Compute the upper quality index (Q_U):

$$Q_U = \frac{USL - X}{s}$$

Where: USL = upper specification limit.

4. Compute the lower quality index (Q_L):

$$Q_L = \frac{X - LSL}{s}$$

Where: LSL = lower specification limit.

5. Determine P_U (percent within the upper specification limit which corresponds to a given Q_U) from Table 106-1.

Note: If a USL is not specified, P_U will be 100.

6. Determine P_L (percent within the lower specification limit which corresponds to a given Q_L) from Table 106-1.
Note: If a LSL is not specified, P_L will be 100.

7. Determine the Quality Level (total percent within specification limits).

$$\text{Quality Level} = (P_U + P_L) - 100$$

8. Determine the Pay Factor (PF) for the lot from Table 106-2 using the Quality Level from step 7.

9. Determine the Composite Pay Factor (CPF) for each lot.

$$\text{CPF} = \frac{[f_1(PF_1) + f_2(PF_2) + \ldots f_j(PF_j)]}{\Sigma f}$$

Where: f_J = price adjustment factor listed in the specifications for the applicable property.
PF_J = Pay Factor for the applicable property.
Σf = Sum of the "f" (price adjustment) factors.

Note: Numbers used in the above calculations shall be carried to significant figures and rounded according to AASHTO Standard Recommended Practice R-11 *(Rounding off method)*.

106.03.3 Random Sampling Locations. The selection of the sampling locations for quality assurance tests must be entirely random. This procedure shall be used for determining the location for taking a sample in order to eliminate any intentional or minimize any unintentional bias on the part of the person taking the sample.

Sampling locations shall be determined on the basis of time, tonnage, volume, distance, area, etc. The only other necessary information is the size of the sublot to be sampled. Random numbers shall be selected using the procedures outlined below. Once the random numbers have been selected they shall be applied to the sublot sizes to determine sampling location.

106.03.3.1 Sampling In-Place Roadway Material: Determine the total length and total width of the sublot. Following method #1 or method #2, pick a random number for each width and length determination. Multiply the random numbers by the width and length to arrive at the sampling location.

Example: A sublot is 5000 ft. long and 12 ft. wide. Using method #1 or method #2, choose a random number, which is then multiplied by 5000. In this instance, the number chosen was 0.376. Thus the sample will be taken at 1880 ft. from the beginning of he sublot. Determine the location from the edge of the pavement by selecting an additional random number, which is then multiplied by 12. In this instance, the number chosen was 0.512. Therefore, the sample should be taken 1880 ft. from the beginning of the sublot and 6 ft. from the designated (right or left) edge of the pavement.

106.03.3.2 Sampling Truck Loads: Determine the quantity that represents a sublot of material. To determine which trucks to sample, choose a random number and multiply this number by the total quantity in the sublot. This will give an indication on when to take the sample.

Example: A sublot of concrete is 50 cy. Using method #1 or method #2, choose a random number, which is then multiplied by 50. In this instance, the number chosen is 01.763. Thus the sample should be taken on the 38th cy of the sublot.

106.03.3.3 Instructions for choosing random numbers.

106.3.3.3.1 Method #1. Table 106-3 consists of all numbers from 0.001 to 1.000. Each number appears only once. To use the table correctly and to eliminate bias, point without looking to a number in the table. It may be advantageous to use a pointer such as a mechanical pencil or a like pointed object. Either page may be used but should be alternated between successive uses.

After picking a number, the basis is established for locating the sought-after number in a more random, unbiased method. Examine the first two digits of the three-digit number chosen. This number locates the line number (the vertical column on the left) to be used in finding the sought-after number. Note: the number 1.000 is invalid for choosing the line number.

Once the line number is chosen, repeat the procedure by choosing another number and, using the first digit, pick the column number (the horizontal numbers at the top of the table). The intersection of the two numbers is the sought-after number.

106.03.3.3.2 Method #2. Random numbers may be obtained by using the random number generator function found on hand-held calculators or computer spreadsheet programs.

Table 106-1 Quality Level Analysis by the Standard Deviation Method

P_U or P_L %*	Upper Quality Index Q_U or Lower Quality Index Q_L														
	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n= 10 to n= 11	n= 12 to n= 14	n= 15 to n= 18	n= 19 to n= 25	n= 26 to n= 37	n= 38 to n= 69	n= 70 to n= 200	n= 201 to n=x
100	1.16	1.50	1.79	2.03	2.23	2.39	2.53	2.65	2.83	3.03	3.20	3.38	3.54	3.70	3.83
99		1.47	1.67	1.80	1.89	1.95	2.00	2.04	2.09	2.14	2.18	2.22	2.26	2.29	2.31
98	1.15	1.44	1.60	1.70	1.76	1.81	1.84	1.86	1.91	1.93	1.96	1.99	2.01	2.03	2.05
97		1.41	1.54	1.62	1.67	1.70	1.72	1.74	1.77	1.79	1.81	1.83	1.85	1.86	1.87
96	1.14	1.38	1.49	1.55	1.59	1.61	1.63	1.65	1.67	1.68	1.70	1.71	1.73	1.74	1.75
95		1.35	1.44	1.49	1.52	1.54	1.55	1.56	1.58	1.59	1.61	1.62	1.63	1.63	1.64
94	1.13	1.32	1.39	1.43	1.46	1.47	1.48	1.49	1.50	1.51	1.52	1.53	1.54	1.55	1.55
93		1.29	1.35	1.38	1.40	1.41	1.42	1.43	1.44	1.44	1.45	1.46	1.46	1.47	1.47
92	1.12	1.26	1.31	1.33	1.35	1.36	1.36	1.37	1.37	1.38	1.39	1.39	1.40	1.40	1.40
91	1.11	1.23	1.27	1.29	1.30	1.30	1.31	1.31	1.32	1.32	1.33	1.33	1.33	1.34	1.34
90	1.10	1.20	1.23	1.24	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28	1.28	1.28
89	1.09	1.17	1.19	1.20	1.20	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.22	1.22	1.23
88	1.07	1.14	1.15	1.16	1.16	1.16	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.13	1.13
86	1.04	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
84	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
83	1.00	0.99	0.98	0.97	0.97	0.96	.096	0.96	0.96	0.96	0.96	0.96	0.95	0.95	0.95
82	0.97	0.96	0.95	0.94	0.93	0.93	0.93	0.92	0.92	0.92	092	0.92	0.92	0.92	0.92
81	0.96	0.93	0.91	0.90	0.90	0.89	0.89	0.89	0.89	0.88	0.88	0.88	0.88	0.88	0.88
80	0.93	0.90	0.88	0.87	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84
79	0.91	0.87	0.85	0.84	0.83	0.82	0.82	0.82	0.82	0.81	0.81	0.81	0.81	0.81	0.81
78	0.89	0.84	0.82	0.80	0.80	0.79	0.79	0.79	0.78	0.78	0.78	0.78	0.77	0.77	0.77
77	0.87	0.81	0.78	0.77	0.76	0.76	0.76	0.75	0.75	0.75	0.75	0.74	0.74	0.74	0.74
76	0.84	0.78	0.75	0.74	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.71	0.71	0.71	0.71
75	0.82	0.75	0.72	0.71	0.70	0.70	0.69	0.69	0.69	0.68	0.68	0.68	0.68	0.68	0.67
74	0.79	0.72	0.69	0.68	0.67	0.66	0.66	0.66	0.66	0.65	0.65	0.65	0.65	0.64	0.64
73	0.76	0.69	0.66	0.65	0.64	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.62	0.61	0.61
72	0.74	0.66	0.63	0.62	0.61	0.60	0.60	0.60	0.59	0.59	0.59	0.59	0.59	0.58	0.58
71	0.71	0.63	0.60	0.59	0.58	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.55	0.55
70	0.68	0.60	0.57	0.56	0.55	0.55	0.54	0.54	0.54	0.53	0.53	0.53	0.53	0.53	0.52
69	0.65	0.57	0.54	0.53	0.52	0.52	0.51	0.51	0.51	0.50	0.50	0.50	0.50	0.50	0.50
68	0.62	0.54	0.51	0.50	0.49	0.49	0.48	0.48	0.48	0.48	0.47	0.47	0.47	0.47	0.47
67	0.59	0.51	0.47	0.47	0.46	0.46	0.46	0.45	0.45	0.45	0.45	0.44	0.44	0.44	0.44
66	0.56	0.48	0.45	0.44	0.44	0.43	0.43	0.43	0.42	0.42	0.42	0.42	0.41	0.41	0.41
65	0.52	0.45	0.43	0.41	0.41	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.39	0.39
64	0.49	0.42	0.40	0.39	0.38	0.38	0.37	0.37	0.37	0.37	0.36	0.36	0.39	0.36	0.36
63	0.46	0.39	0.37	0.36	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.33
62	0.43	0.36	0.34	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.31
61	0.39	0.33	0.31	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.28	0.28	0.28	0.28	0.28
60	0.36	0.30	0.28	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25
59	0.32	0.27	0.25	0.25	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.23	0.23
58	0.29	0.24	0.23	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20
57	0.25	0.21	0.20	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
56	0.22	0.18	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15
55	0.18	0.15	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
54	0.14	0.12	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
53	0.11	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
52	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
51	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: For negative values of Q_U or Q_L, P_U or P_L is equal to 100 minus the table value for P_U or P_L. If the value of Q_U or Q_L does not correspond exactly to a figure in the table, use the next higher figure.

*Within limits for positive values of Q_U or Q_L.

Table 106-2. PAY FACTORS

Pay Factor	Required Quality Level for a Given Sample Size(n) and Given Pay Factor														
	n= 3	n= 4	n= 5	n= 6	n= 7	n= 8	n= 9	n= 10 to n= 11	n= 12 to n= 14	n= 15 to n= 18	n= 19 to n= 25	n= 26 to n= 37	n= 38 to n= 69	n= 70 to n= 200	n= 201 to n= x
1.05	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1.04	90	91	92	93	93	93	94	94	95	95	96	96	96	97	99
1.03	80	85	87	88	89	90	91	91	92	93	93	94	95	96	97
1.02	75	80	83	85	86	87	88	88	89	90	91	92	93	94	95
1.01	71	77	80	82	84	85	85	86	87	88	89	90	91	93	94
100	68	74	78	80	81	82	83	84	85	86	87	89	90	91	93
0.99	66	72	75	77	79	80	81	82	83	85	86	87	88	90	92
0.98	64	70	73	75	77	78	79	80	81	83	84	85	87	88	90
0.97	62	68	71	74	75	77	78	78	80	81	83	84	85	87	89
0.96	60	66	69	72	73	75	76	77	78	80	81	83	84	86	88
0.95	59	64	68	70	72	73	74	75	77	78	80	81	83	85	87
0.94	57	63	66	68	70	72	73	74	75	77	78	80	81	83	86
0.93	56	61	65	67	69	70	71	72	74	75	77	78	80	82	84
0.92	55	60	63	65	67	69	70	71	72	74	75	77	79	81	83
0.91	53	58	62	64	66	67	68	69	71	73	74	76	78	80	82
0.90	52	57	60	63	64	66	67	68	70	71	73	75	76	79	81
0.89	51	55	59	61	63	64	66	67	68	70	72	73	75	77	80
0.88	50	54	57	60	62	63	64	65	67	69	70	72	74	76	79
0.87	48	53	56	58	60	62	63	64	66	67	69	71	73	75	78
0.86	47	51	55	57	59	60	62	63	64	66	68	70	72	74	77
0.85	46	50	53	56	58	59	60	61	63	65	67	69	71	73	76
0.84	45	49	52	55	56	58	59	60	62	64	65	67	69	72	75
0.83	44	48	51	53	55	57	58	59	61	63	64	66	68	71	74
0.82	42	46	50	52	54	55	57	58	60	61	63	65	67	70	72
0.81	41	45	48	51	53	54	56	57	58	60	62	64	66	69	71
0.80	40	44	47	50	52	53	54	55	57	59	61	63	65	67	70
0.79	38	43	46	48	50	52	53	54	56	58	60	62	64	66	69
0.78	37	41	45	47	49	51	52	53	55	57	59	61	63	65	68
0.77	36	40	43	46	48	50	51	52	54	56	57	60	62	64	67
0.76	34	39	42	45	47	48	50	51	53	55	56	58	61	63	66
0.75	33	38	41	44	46	47	49	50	51	53	55	57	59	62	65

NOTE: To obtain a given pay factor, the computed Quality Level shall equal or exceed the value in the table.

Delete Pay Factor rows more than 1.0 where quality incentives are not allowed.

Table 106-3 (a) TABLE OF RANDOM NUMBERS

	0	1	2	3	4	5	6	7	8	9
0	0.272	0.519	0.098	0.459	1.000	0.554	0.250	0.246	0.736	0.432
1	0.994	0.978	0.693	0.593	0.690	0.028	0.831	0.319	0.073	0.268
2	0.039	0.449	0.737	0.501	0.960	0.254	0.239	0.474	0.031	0.720
3	0.144	0.695	0.339	0.621	0.128	0.032	0.413	0.617	0.764	0.257
4	0.312	0.138	0.670	0.894	0.682	0.061	0.832	0.765	0.226	0.745
5	0.871	0.838	0.595	0.576	0.096	0.581	0.245	0.786	0.412	0.867
6	0.783	0.874	0.795	0.430	0.265	0.059	0.260	0.563	0.632	0.394
7	0.358	0.424	0.684	0.074	0.109	0.345	0.618	0.176	0.352	0.748
8	0.494	0.839	0.337	0.325	0.699	0.083	0.043	0.809	0.981	0.499
9	0.642	0.514	0.297	0.869	0.744	0.824	0.524	0.656	0.608	0.408
10	0.485	0.240	0.292	0.335	0.088	0.589	0.127	0.396	0.401	0.407
11	0.728	0.819	0.557	0.050	0.152	0.816	0.404	0.079	0.703	0.493
12	0.029	0.262	0.558	0.159	0.767	0.175	0.979	0.521	0.781	0.843
13	0.918	0.348	0.311	0.232	0.797	0.921	0.995	0.225	0.397	0.356
14	0.641	0.013	0.780	0.478	0.529	0.520	0.093	0.426	0.323	0.504
15	0.208	0.468	0.045	0.798	0.065	0.315	0.318	0.742	0.597	0.080
16	0.346	0.429	0.537	0.469	0.697	0.124	0.541	0.525	0.281	0.962
17	0.900	0.206	0.539	0.308	0.480	0.293	0.448	0.010	0.836	0.233
18	0.228	0.369	0.513	0.762	0.952	0.856	0.574	0.158	0.689	0.579
19	0.746	0.170	0.974	0.306	0.145	0.139	0.417	0.195	0.338	0.901
20	0.363	0.103	0.931	0.389	0.199	0.488	0.915	0.067	0.878	0.640
21	0.663	0.942	0.278	0.785	0.638	0.002	0.989	0.462	0.927	0.186
22	0.545	0.185	0.054	0.198	0.717	0.247	0.913	0.975	0.555	0.559
23	0.360	0.349	0.569	0.910	0.420	0.492	0.947	0.115	0.884	0.452
24	0.789	0.815	0.464	0.484	0.020	0.007	0.547	0.941	0.365	0.261
25	0.279	0.609	0.086	0.852	0.890	0.108	0.076	0.089	0.662	0.607
26	0.680	0.235	0.706	0.827	0.572	0.769	0.310	0.036	0.329	0.477
27	0.078	0.444	0.178	0.651	0.423	0.672	0.517	0.660	0.657	0.972
28	0.676	0.830	0.531	0.888	0.305	0.421	0.307	0.502	0.112	0.808
29	0.861	0.899	0.643	0.771	0.037	0.241	0.582	0.578	0.634	0.077
30	0.111	0.364	0.970	0.669	0.548	0.687	0.639	0.510	0.105	0.549
31	0.289	0.857	0.948	0.980	0.132	0.094	0.298	0.870	0.309	0.441
32	0.961	0.893	0.392	0.377	0.864	0.472	0.009	0.946	0.766	0.287
33	0.637	0.986	0.753	0.566	0.213	0.807	0.017	0.460	0.515	0.630
34	0.834	0.121	0.255	0.453	0.376	0.583	0.422	0.371	0.399	0.366
35	0.284	0.490	0.402	0.151	0.044	0.436	0.747	0.694	0.136	0.585
36	0.038	0.814	0.594	0.911	0.324	0.322	0.895	0.411	0.160	0.367
37	0.351	0.283	0.027	0.220	0.685	0.527	0.943	0.556	0.853	0.612
38	0.143	0.384	0.645	0.479	0.489	0.052	0.187	0.990	0.912	0.750
39	0.512	0.056	0.018	0.122	0.303	0.803	0.553	0.729	0.205	0.925
40	0.296	0.705	0.156	0.616	0.534	0.168	0.564	0.866	0.739	0.850
41	0.451	0.536	0.768	0.518	0.481	0.880	0.835	0.734	0.427	0.847
42	0.837	0.405	0.591	0.370	0.104	0.848	0.004	0.414	0.354	0.707
43	0.724	0.153	0.841	0.829	0.470	0.391	0.388	0.163	0.817	0.790
44	0.665	0.825	0.671	0.623	0.770	0.400	0.068	0.440	0.019	0.944
45	0.573	0.716	0.266	0.456	0.434	0.467	0.603	0.169	0.721	0.779
46	0.332	0.702	0.300	0.570	0.945	0.968	0.649	0.097	0.118	0.242
47	0.755	0.951	0.937	0.550	0.879	0.162	0.791	0.810	0.625	0.674
48	0.439	0.491	0.855	0.446	0.773	0.542	0.416	0.350	0.957	0.419
49	0.700	0.877	0.442	0.286	0.526	0.071	0.154	0.988	0.333	0.626

Table 106-3 (b) TABLE OF RANDOM NUMBERS

	0	1	2	3	4	5	6	7	8	9
50	0.523	0.613	0.752	0.733	0.528	0.072	0.820	0.929	0.777	0.461
51	0.905	0.182	0.567	0.249	0.227	0.229	0.604	0.304	0.217	0.142
52	0.373	0.120	0.602	0.793	0.692	0.863	0.954	0.873	0.107	0.675
53	0.057	0.953	0.041	0.090	0.223	0.508	0.806	0.438	0.203	0.586
54	0.967	0.040	0.708	0.271	0.189	0.342	0.740	0.801	0.985	0.263
55	0.917	0.715	0.758	0.005	0.666	0.599	0.934	0.100	0.987	0.085
56	0.131	0.646	0.659	0.047	0.051	0.562	0.435	0.731	0.362	0.317
57	0.326	0.605	0.443	0.601	0.386	0.560	0.378	0.172	0.445	0.636
58	0.299	0.106	0.237	0.732	0.796	0.476	0.099	0.804	0.735	0.950
59	0.101	0.055	0.776	0.686	0.171	0.533	0.936	0.095	0.982	0.211
60	0.267	0.598	0.754	0.658	0.274	0.215	0.177	0.218	0.330	0.628
61	0.471	0.102	0.454	0.568	0.963	0.357	0.882	0.507	0.157	0.580
62	0.535	0.881	0.014	0.966	0.958	0.190	0.180	0.759	0.433	0.355
63	0.277	0.458	0.295	0.196	0.772	0.148	0.466	0.291	0.688	0.046
64	0.719	0.167	0.181	0.653	0.328	0.070	0.015	0.155	0.631	0.063
65	0.385	0.858	0.713	0.883	0.916	0.084	0.561	0.999	0.379	0.668
66	0.862	0.928	0.822	0.812	0.977	0.395	0.788	0.920	0.673	0.698
67	0.486	0.938	0.757	0.749	0.991	0.219	0.264	0.932	0.898	0.006
68	0.091	0.872	0.959	0.922	0.727	0.811	0.075	0.374	0.133	0.730
69	0.146	0.482	0.930	0.611	0.179	0.011	0.248	0.886	0.344	0.926
70	0.709	0.184	0.390	0.409	0.191	0.117	0.860	0.135	0.406	0.134
71	0.996	0.896	0.760	0.347	0.053	0.372	0.193	0.756	0.565	0.914
72	0.971	0.859	0.147	0.114	0.418	0.889	0.792	0.064	0.652	0.288
73	0.202	0.538	0.026	0.949	0.696	0.008	0.846	0.259	0.415	0.425
74	0.212	0.321	0.778	0.940	0.496	0.231	0.664	0.903	0.473	0.909
75	0.207	0.799	0.487	0.022	0.813	0.891	0.500	0.368	0.725	0.437
76	0.818	0.503	0.906	0.224	0.904	0.892	0.455	0.343	0.924	0.197
77	0.701	0.984	0.174	0.141	0.704	0.908	0.048	0.828	0.997	0.058
78	0.035	0.380	0.001	0.381	0.251	0.497	0.214	0.794	0.552	0.588
79	0.221	0.200	0.587	0.353	0.584	0.270	0.885	0.110	0.956	0.711
80	0.647	0.403	0.530	0.738	0.280	0.457	0.650	0.276	0.661	0.973
81	0.667	0.722	0.327	0.723	0.410	0.635	0.012	0.907	0.316	0.677.
82	0.644	0.590	0.021	0.269	0.042	0.062	0.387	0.183	0.964	0.544
83	0.302	0.123	0.116	0.282	0.851	0.256	0.648	0.845	0.782	0.993
84	0.633	0.933	0.331	0.546	0.842	0.016	0.236	0.164	0.923	0.976
85	0.060	0.681	0.683	0.775	0.624	0.955	0.126	0.655	0.919	0.113
86	0.165	0.532	0.431	0.341	0.092	0.244	0.222	0.336	0.034	0.216
87	0.875	0.691	0.383	0.382	0.596	0.301	0.275	0.188	0.868	0.805
88	0.726	0.902	0.252	0.130	0.238	0.398	0.763	0.463	0.615	0.140
89	0.273	0.393	0.285	0.161	0.619	0.865	0.551	0.030	0.571	0.258
90	0.253	0.821	0.600	0.023	0.606	0.849	0.610	0.577	0.082	0.774
91	0.340	0.654	0.173	0.495	0.498	0.992	0.192	0.506	0.751	0.129
92	0.194	0.290	0.592	0.983	0.509	0.998	0.522	0.627	0.741	0.540
93	0.166	0.450	0.210	0.204	0.840	0.826	0.833	0.516	0.965	0.375
94	0.712	0.314	0.033	0.823	0.629	0.939	0.887	0.066	0.743	0.081
95	0.622	0.800	0.710	0.575	0.678	0.465	0.802	0.969	0.150	0.784
96	0.313	0.294	0.897	0.718	0.614	0.876	0.025	0.049	0.620	0.125
97	0.137	0.087	0.003	0.483	0.201	0.209	0.320	0.935	0.447	0.787
98	0.243	0.679	0.844	0.069	0.024	0.543	0.714	0.234	0.505	0.428
99	0.361	0.359	0.230	0.761	0.334	0.149	0.511	0.475	0.854	0.119

1/13/97 - DRAFT (Revisions since 12/13/96)

Supersedes Spec. Prov.
Dated 6/29/94, & 6/15/95
Supersedes Suppl Spec.
Dated 01/07/94, 02/24/94

Project ____________________

Fed. No. ____________________

State No. ____________________

Date ____________________

SPECIAL PROVISION

AMENDMENT TO SECTION 401 -- PLANT MIX PAVEMENTS - GENERAL

Items 403.XXXX2 - Hot Bituminous Pavement, __________ (QC/QA)
Items 404.XXXX2 - Recycled Hot Bituminous Pavement (QC/QA)

Amend 1.1 to read:

1.1 These specifications include general requirements that are applicable to all types of plant mix asphalt pavements irrespective of gradation of aggregate, kind and amount of asphalt cement, or pavement use. Deviations from these general requirements will be indicated in the specific requirements for each type.

Amend 1.2 to read:

1.2 These specifications allow the use of reclaimed asphalt pavement material.

Amend 1.3 to read:

1.3 This work shall consist of one or more courses of asphalt pavement constructed on a prepared foundation in accordance with these specifications and the specific requirements of the type under contract. The work shall be in reasonably close conformity with the lines, grades, thickness, and typical cross sections shown on the plan, within the tolerances specified, or established by the Engineer.

Add to 1.3:

1.3.1 The work will be accepted under Quality Assurance (QA) provisions in accordance with these Specifications and the applicable requirements of 106.

Amend the last sentence in 2.1 to read:

Sufficient material shall be available prior to starting daily operations to insure uninterrupted processing for the working day.

Delete 2.1.1.1

Amend 2.1.2 to read:

2.1.2 Fine aggregate shall consist of sound durable particles of sand, crushed stone or a combination thereof. Fine aggregate shall be free from clay balls and injurious amounts of organic matter. Stone screening shall be produced from stone at least equal in quality to that specified for coarse aggregate.

Amend 2.2 to read:

2.2 Asphalt cement shall meet the requirements of AASHTO M 226 Table 2, as shown in 702, Table 1. The grade to be used shall be as ordered.

Delete 2.3.

Amend the first sentence in 2.4 to read:

Hot asphalt mix shall be composed of a mixture of aggregate, filler if required, and asphalt cement.

Amend 2.4.1 to read:

2.4.1 Job mix formula submission. At least 21 calendar days prior to production, the Contractor shall submit to the Bureau of Materials and Research for approval, a job mix formula for each hot asphalt mix to be produced from each plant. Each approved job mix formula may be used for production on more than one project. Copies of the approved job mix formula shall be sent to the Bureau of Materials and Research showing project name and number for each project prior to production.

The general composition limits given in Table 1 indicate target value ranges of mixtures permissible under this specification. The job mix formula shall lie within the target value ranges indicated for the particular type of hot asphalt mix. The following shall be included with each job mix formula:

A) Aggregate and mineral filler
   1) Target value for percent passing each sieve size for the aggregate blend.
   2) Source and percentage of each aggregate stockpile to be used.

3) Average gradation of each aggregate stockpile.
4) Representative samples for each aggregate stockpile:
   a) 50 lbs of each aggregate
   b) 20 lbs of mineral filler such as lime stone, filler earth, etc. that is proposed to improve gradation characteristics or mix performance.

B) Asphalt cement
1) A single percentage of asphalt cement to be added to the aggregate.
2) Four 1 quart samples of asphalt cement to be used in the mixture.
3) Recent quality test results from the manufacturer for the asphalt cement including a temperature-viscosity curve.
4) Material safety data sheets.

C) Antistrip additives. When applicable, furnish:
1) One pint sample of liquid heat-stable antistrip additive or a 10 lbs sample of dry antistrip additive such as hydrated limes, Portland cement, etc. that is proposed, including name of product, manufacturer, and manufacturer's data sheet.
2) Material safety data sheet.

D) A temperature range at which the hot asphalt mix is to be mixed, and

E) A recommended temperature range for compaction.

Amend Table 2 - Composition of Mixtures - Master Ranges to read:

Table 1 - COMPOSITION OF MIXTURES - TARGET VALUE RANGES(1)

	BASE COURSES(2)			WEARING COURSES		
SIEVE SIZE	TYPE A: 1-1/4"	TYPE B: 3/4"	TYPE C: 1/2"	TYPE D: 3/4"	TYPE E: 1/2"	TYPE F: 3/8"
	PERCENT PASSING BY WEIGHT - COMBINED AGGREGATE					
1-1/4"	98.0 - 100.0					
1"	82.0 - 88.0					
3/4"	66.0 - 80.0	98.0 - 100.0		98.0 - 100.0		
1/2"	54.0 - 66.0	74.0 - 88.0	98.0 - 100.0	86.0 - 96.0	98.0 - 100.0	
3/8"	46.0 - 56.0	64.0 - 76.0	69.0 - 81.0	72.0 - 86.0	89.0 - 91.0	98.0 - 100.0
No. 4	32.0 - 41.0	46.0 - 53.0	42.0 - 46.0	54.0 - 75.0	62.0 - 71.0	68.0 - 76.0
No. 10	20.0 - 25.0	30.0 - 36.0	30.0 - 34.0	38.0 - 65.0	40.0 - 48.0	46.0 - 53.0
No. 20	12.0 - 16.0	18.0 - 22.0	18.0 - 22.0		26.0 - 30.0	27.0 - 33.0
No. 40	7.0 - 11.0	11.0 - 15.0	11.0 - 15.0	19.0 - 42.0	16.0 - 21.0	17.0 - 23.0
No. 80	3.0 - 7.0	5.0 - 9.0	5.0 - 9.0	11.0 - 27.0	8.0 - 12.0	8.0 - 14.0
No. 200	1.0 - 3.0	1.0 - 3.0	1.0 - 3.0	4.0 - 7.0	3.0 - 5.0	3.0 - 5.0
Asphalt Cement: % of Mix(3)	4.10 - 4.50	5.10 - 5.70	5.30 - 5.50	5.80 - 6.20	6.00 - 6.7.10	6.20 - 6.70

(1) Gradings approaching the maximum amount permitted to pass the various sieves will result in pavement surfaces having comparatively fine texture, while gradings approaching the minimum amounts passing the various sieves will result in surfaces with comparatively coarse textures.

(2) Alternate aggregate sizes are included to provide that generally the coarse aggregate shall not be larger than one-half the thickness of the layer being placed.

(3) The asphalt content for the above mixture is based on the use of aggregate with a specific gravity of 2.65 to 2.70. The asphalt content will be adjusted when aggregate with a higher specific gravity is used.

Amend 2.4.1.1 to read:

2.4.1.1 After the *additional* job mix formula is established, all mixtures furnished for the project shall conform thereto, within the gradation and asphalt cement content reject limits in Table 5 in 3.14.1. Limits for price adjustments under quality assurance provisions shall be as set forth in Table 4 in 3.14.1.

Mix designs submitted by the Contractor shall yield a Marshall stability of not less than 1200 pounds, a flow value between 8 and 16, and a void content of the compacted mixture between 3 and 9 percent. The Marshall values indicated shall be determined in accordance with AASHTO T 245. The hot asphalt mix shall be mixed at ±20 degrees Fahrenheit from design temperature.

Amend 2.4.1.2 to read:

2.4.1.2 If it becomes necessary to change the asphalt cement grade or the source of aggregate, a new job mix formula shall be developed. Up to 14 calendar days will be required to evaluate a change. Approved changes in target values will not be applied retroactively for acceptance or payment. If it becomes necessary to change the source of asphalt cement, the Contractor must submit recent quality test results from the manufacturer for the asphalt cement including a temperature viscosity curve.

Amend 2.4.1.3 to read:

2.4.1.3 The quantity of asphalt cement is a percentage by weight of the total mixture. The amount of asphalt cement required for a given mixture should be determined by appropriate laboratory testing or on the basis of past experience with similar mixtures, or by a combination of both.

Add to 2.4.1:

2.4.1.4 The Contractor shall have the option of utilizing asphalt pavement removed under the contract, if any, or old asphalt pavement from an existing stockpile or supplying all new materials for the production of asphalt pavement or any combination of the foregoing. If the job mix formula uses recycled materials, the mix shall meet the requirements of Reclaimed Asphalt Pavement as specified in 401.2.7.

2.4.1.5 The laboratory performing the design shall be approved by the Department. To obtain the Departments approval, a laboratory must demonstrate that they are equipped, staffed, and managed, so as to be able to produce job mix formulas and test hot asphalt mix in accordance with these Specifications. Approval for each laboratory shall remain in effect for a period of one year.

Amend 2.5 to read:

2.5 Polyester fibers for bridge pavement base course shall be of a type on the Approved Products List maintained by the Bureau of Materials and Research.

Delete 2.5.1 and 2.5.2.

Amend 2.7 to read:

2.7 Reclaimed Asphalt Pavement (RAP). RAP shall consist of asphalt pavement and shall be processed by crushing, cold milling or other approved sizing techniques approved by the Bureau of Materials and Research to meet the required gradation specifications. The mixture of RAP, new aggregate and added asphalt cement shall meet the requirements specified in Table 1, Composition of Mixtures for aggregate gradation and asphalt cement content. The added asphalt cement may be AC 5, AC 10, or other asphalt cement grades as designated by the Bureau of Materials and Research. The aggregate component of the pavement (RAP), shall meet the requirements of Section 401.2.1. The asphalt component of the RAP shall be asphalt cement and shall be free of significant contents of solvents, tars and other volatile organic compounds or foreign substances that will make the RAP unacceptable for recycling as determined by the Bureau of Materials and Research. The Bureau of Materials and Research will use one of the following procedures to approve the RAP quality.

a) RAP obtained from a pavement, which was constructed with asphalt cement, and aggregates that meet the current requirements of Section 401.2.1, shall be approved by the Bureau of Materials and Research.

b) If the source of the RAP or its quality is not known, the Contractor shall submit for approval to the Bureau of Materials and Research at least 30 calendar days prior to the start of paving the following:

1. The designated use of the RAP and approximate proportions.
2. Representative samples and gradation and asphalt cement content test results of the RAP to be incorporated into the recycled mixture. Two samples shall be taken from each 1000 tons or less of stockpiled material.

3. Penetration, Kinematic Viscosity and Viscosity by Vacuum Capillary Viscometer test results of the recovered asphalt cement. A minimum of one test for each 1000 tons or less of stockpiled material, certified by an independent lab.

Amend 2.8 to read:

2.8 Asphalt modifiers. Admixtures and additives shall be approved by the Administrator of the Bureau of Materials and Research.

Amend 3.1.1 to read:

3.1.1 Mixing plants shall conform to AASHTO M 156. An efficient dust collecting system shall be provided to prevent the loss of fine material. The material collected may be returned to the mixture at a uniform rate or discarded.

Delete 3.1.1.1 through 3.1.2.5

Amend 3.1.3.2 to read:

3.1.3.2 The Engineer shall have access at any time to all parts of the plant for inspection of the conditions and operations of the plant, for confirmation of the adequacy of the equipment in use, for verification of proportions and character of materials, and for determination of temperatures being maintained in the preparation of the mixtures. The Contractors shall provide a suitable building, room, or trailer for exclusive use as a testing laboratory in which to house and use the testing equipment. Priority use of the testing equipment shall be given to acceptance testing. Laboratories shall be in an approved location. Unless otherwise approved, one laboratory shall be provided for each plant.

Amend 3.1.3.3 to read:

3.1.3.3 Testing Laboratories shall meet the following minimum requirements:

Outside Dimensions:	16 feet long by 8 feet wide (or equal), by 7 feet high.
Windows:	2, with locks and screens, providing cross ventilation.
Doors:	1 with lock and screen.
Electrical:	Adequate lighting and power outlets.
Air Conditioner:	Unit size shall be as recommended for size of facility.
Heat:	Thermostatically controlled to maintain a minimum of 68 degrees F.
Weatherproofing:	Roof, sides and floor shall be maintained weatherproof at all times.
Appurtenances:	

a) An exhaust fan and hood over hot plates and extractor. The hood shall be large enough to cover both the hot plates and the extractor; the fan shall be a high volume axial flow fan, at least 10 inches in diameter and of sufficient capacity to adequately vent the fumes.
b) Free wall space of at least 12 square feet; or a bulletin board of equal area for posting notices and job mix formulas.
c) Suitable shelves and benches. One bench shall be ±24 inches wide, by ±36 inches high, at least 10 feet long. The bench may extend the length of the building.

Amend 3.1.3.4 (a) to read:

(a) Electronic balance with tray, at least 9000 gram net capacity, sensitive to 0.1 gram.

Delete 3.1.3.4 (h).

Amend 3.1.3.4 (r) to read:

(r) Microwave oven, minimum 1 cubic foot capacity, 700 watts.

Delete 3.1.3.4 (t).

Add the following to 3.1.3.4:

(x) Equipment sufficient to perform AASHTO T 209.

Delete 3.1.4 through 3.1.7.13.

Amend 3.2.1 to read:

3.2.1 The job mix formula temperature may be adjusted within the limits of 260 degrees F and 350 degrees F according to the existing conditions. Material with a temperature at discharge outside the job mix formula tolerance may be rejected. In no case will a mixture be accepted with a discharge temperature in excess of 375 degrees F.

Delete 3.3 through 3.3.7.

Amend the words "bitumen" with the words "asphalt cement" in 3.4.4 (b) and (d).

Amend 3.4.5 to read:

3.4.5 Each weight slip will show a consecutive load number and shall include accumulative total of material delivered for each day.

Amend 3.4.6 to read:

3.4.6 The inside surfaces of vehicles may be lightly lubricated with a soap solution or a non petroleum release agent that will not be detrimental to the mix. Equipment which leaks oil, diesel fuel, gasoline, or any other substance detrimental to the pavement will not be allowed on the project.

Amend the third sentence of 3.5.2 to read:

No load shall be sent out so late in the day that spreading and compaction cannot be completed during the daylight, unless night work is specified.

Amend the fifth sentence of 3.5.2 to read:

Wearing course shall not be scheduled for placement after October 1st of any year without written approval by the Engineer.

Add the following sentence after the fifth sentence of 3.5.2:

If it is determined to be in the best interest of the Department to schedule placement after October 1st the above specified weather and surface conditions shall remain in effect.

Amend 3.5.3 to read:

3.5.3 At the beginning and end of the project or project section, the existing pavement shall be removed to a sufficient depth to allow the placing of the new pavement and construction of a transverse joint, which shall be painted with a suitable bituminous material. The underlying course shall be clean and free from foreign materials and loose asphalt pavement patches and must present a dry, unloading surface.

Amend 3.5.5 to read:

3.5.5 Tack coat. Tack coat shall be applied in accordance with 410.3.

Amend 3.5.7 to read:

3.5.7 Pavers. Pavers shall be:

(a) Self-contained, power propelled units with adjustable vibratory secrets with full-width screw augers.

(b) Heated for the full width of the screed.

(c) Capable of spreading and finishing courses of hot asphalt mix in widths at least 12 inches more than the width of one lane.

(d) Equipped with a receiving hopper having sufficient capacity to ensure a uniform spreading operation.
(e) Equipped with automatic feed controls, which are properly adjusted to maintain a uniform depth of material ahead of the screed.
(f) Capable of being operated at forward speeds consistent with satisfactory laying of the mix.
(g) Capable of producing a finished surface of the required smoothness and texture without segregating, tearing, shoving, or gouging the mixture.
(h) Equipped with automatic screed controls with sensors capable of sensing the transverse slope of the screed, and providing the automatic signals that operate the screed to maintain grade and transverse slope from a reference such as a grade wire or ski type device (floating beam) with a minimum length of 30 feet.

Delete 3.5.7.1 through 3.5.7.4.

Amend 3.5.7.5 to read:

3.5.7.5 At the start of a days paving, a paver will not be used unless the automatic controls are in working condition. If a breakdown or malfunction occurs sometime during that days production, the equipment may be operated manually only for the remainder of the normal working day on which the breakdown or malfunction occurred. This method of operation must meet all other specifications and will still be bound by quality assurance specifications.

Delete 3.5.7.6 through 3.5.8.

Amend the first sentence in 3.5.9 to read:

When patching existing pavement, hot asphalt mix shall be placed on the prepared clean underlying surface at the locations designated and spread to produce a smooth and uniform patch.

Delete 3.5.13.

Amend 3.6.1 to read:

3.6.1 Immediately after the hot asphalt mix has been spread, struck off, and surface irregularities adjusted, it shall be thoroughly and uniformly compacted. The completed course shall be free from ridges, ruts, humps, depressions, objectionable marks, or irregularities and in conformance with the line, grade, and cross-section shown in the Plans or as established by the Engineer. If necessary, the mix design may be altered to achieve desired results.

Amend 3.6.2 to read:

3.6.2 All compaction units shall be operated at the speed, within manufacturers recommended limits, that will produce the required compaction. The use of equipment which results in excessive crushing of the aggregate will not be permitted. Any asphalt pavement that becomes loose, broken, contaminated, shows an excess or deficiency of asphalt cement, or is in any way defective, shall be removed and replaced at no additional cost with fresh hot asphalt mix which shall be immediately compacted to conform with the surrounding area. Hot asphalt mix shall not be permitted to adhere to the roller drums during rolling.

Amend 3.6.3 to read:

3.6.3 The type of rollers to be used and their relative position in the compaction sequence shall be the Contractor's option, provided specification densities are attained and with the following stipulations:

(a) At least one roller shall be pneumatic-tired.
(b) A vibratory or steel wheel roller shall precede pneumatic tired rolling.
(c) Vibratory rollers shall not be operated in the vibratory mode under the following conditions;
When checking or cracking of the mat occurs, when fracturing of aggregate occurs, and on bridge decks.

Delete 3.6.4 through 3.6.8.

Amend the second sentence in 3.7.1 to read:

Material not trimmed away shall be packed against the lane by means of lutes, leaving a uniform joint.

Delete 3.8. and 3.8.1.

Amend 3.11.1 to read:

3.11.1 Any asphalt material remaining on exposed surfaces of curbs, sidewalks, or other structures shall be removed.

Add to Construction Requirements:

3.12 Quality Control.

3.12.1 The Contractor shall operate in accordance with a Quality Control Plan, hereinafter referred to as the "Plan", sufficient to assure a product meeting the contract requirements. The plan shall meet the requirements of 106.03.1 and these special provisions.

3.12.2 The Plan shall address all elements which affect the quality of the Plant Mix Pavement including, but not limited to, the following:

(a) Job mix formula(so)
(b) Hot asphalt mix plant details.
(c) Stockpile Management.
(d) Make & type of paver(so).
(e) Make & type of rollers including weight, weight per inch of steel wheels, and average ground contact pressure for pneumatic tired rollers.
(f) Name of Plan Administrator.
(g) Name of Process Control Technician(s).
(h) Name of Quality Control Technician(s).
(I) Mixing & Transportation.
(j) Process Control Testing (See Appendix A for example).
(k) Placing sequence and placing procedure for slope, grade control and ride quality.

3.12.3 The Plan shall include the following personnel performing the described functions and meeting the following minimum requirements and qualifications:

(a) **Plan Administrator** meeting one of the following qualifications:

1) Professional Engineer with one year of highway experience acceptable to the Department.
2) Engineer-In-Training with two years of highway experience acceptable to the Department.
3) An individual with three years highway experience acceptable to the Department and with a Bachelor of Science Degree in Civil Engineering Technology or Construction.

4) An individual with five years of Paving experience acceptable to the Department.

(b) **Process Control Technician(s) (PCT)** shall utilize test results and other quality control practices to assure the quality of aggregates and other mix components and control proportioning to meet the job mix formula(s). The PCT shall periodically inspect all equipment used in mixing to assure it is operating properly and that mixing conforms to the mix design(s) and other contract requirements. The Plan shall detail how these duties and responsibilities are to be accomplished and documented and whether more than one PCT is required. The Plan shall include the criteria utilized by the PCT to correct or reject unsatisfactory materials. The PCT shall be certified as a Level I Plant Technician by the New England States Technician Certification Program or have HMA and testing experience acceptable to the Department.

(c) **Quality Control Technician(s) (QCT)** shall perform and utilize quality control tests at the job site to assure that delivered materials meet the requirements of the job mix formula(s). The QCT shall inspect all equipment utilized in transporting, laydown, and compacting to assure it is operating properly and that all laydown and compaction conform to the contract requirements. The plan shall detail how these duties and responsibilities are to be accomplished and documented, and whether more than one QCT is required. The Plan shall include the criteria utilized by the QCT to correct or reject unsatisfactory materials. The QCT shall be *certified* as a Level 1 HMA *Paving* Technician as certified by the New England States Technician Certification Program or have HMA and testing experience acceptable to the Department.

3.12.4 The Plan shall detail the coordination of the activities of the Plan Administrator, the PCT and the QCT. The Plan shall also detail who has the responsibility to reject material, halt production or stop placement.

3.12.5 Asphalt pavement shall be sampled, tested, and evaluated by the Contractor in accordance with the minimum process control guidelines in Table 2.

Table 2 - MINIMUM PROCESS CONTROL GUIDELINES

PROPERTIES	TEST FREQUENCY	TEST METHOD
Temperature of Mix	6 per day at paver hopper and plant	
Surface Temperature	As needed	
Temperature of Mat	4 per day	
Density	1 per 500 Tons or minimum 2 per day	AASHTO T-230 or ASTM D-2950 (Core or Nuclear)
Maximum Theoretical Specific Gravity	1 per day of operation	AASHTO T-209
Aggregate Gradation & Fractured Faces	1 per day	AASHTO T-11 & AASHTO T-27
Asphalt Cement content	1 per 500 tons recommended	AASHTO T-164
Asphalt Cement	As needed	AASHTO M-226
Cross Slope	As needed	

3.12.6 The Contractor may utilize innovative equipment or techniques not addressed by the specifications or these provisions to produce or monitor the production of the mix, subject to approval by the Engineer.

3.13 Quality Assurance.

3.13.1 Asphalt pavement designated for acceptance under Quality Assurance (QA) provisions will be sampled once per sublot on a statistically random basis, tested, and evaluated by the Department in accordance with 106.03.2 and the acceptance testing schedule in Table 3.

Table 3 - ACCEPTANCE TESTING SCHEDULE

PROPERTIES	POINT OF SAMPLING	LOT SIZE	SUBLOT SIZE	TEST METHOD
Gradation	Behind paver & before rolling	~~Job mix formula~~ *401.3.13.2.1*	750 tons	AASHTO T-11 & AASHTO T-27
Asphalt Cement content	Behind paver & before rolling	~~Job mix formula~~ *401.3.13.2.1*	750 tons	AASHTO T-164
Maximum theoretical specific gravity	*Compacted Roadway[1] Core*		750 tons	AASHTO T-209
Air voids in total mix	Compacted roadway[1] core	~~Job mix formula~~ *401.3.13.2.1*	750 tons	AASHTO T-269
Viscosity	*in line*	Tanker load	Tanker load	AASHTO T-202
Thickness[2]	Compacted roadway[1] core	Total project	750 tons	ASTM 3549
Ride *smoothness*	Completion of wearing surface	Total project	0.1 lane mile	401.3.14.5
Cross Slope[3]	*Completion of Wearing Surface*	*Total Project*	*500 ft per Travel Lane*	*401.3.14.6*

(1) Excluding bridge pavements.
(2) Measurements taken from full depth cores obtained for air voids determination.
(3) Cross slope will not be measured on projects where cross slope is not shown on the plans.

3.13.2 Lot Size. For purposes of evaluating all acceptance test properties a lot shall consist of the total quantity represented by each item listed under the lot size heading in the table above. Each lot will be broken down into at least 3 sublots.

The Contractor may request a change in the mix formula. If the request is approved, all of the material produced prior to the change will be evaluated on the basis of available tests and a new lot will begin.

3.13.2.1 A lot for Gradation, Asphalt Content and Air Voids shall be the total quantity represented by the job mix formula with the following exception; When shoulders are a different *thickness than the traveled lane, the quantity represented by the job mix formula covering the shoulder shall be evaluated as a separate lot.*

3.13.3 Sublot size. The quantity represented by each sample will constitute a sublot. The size of each sublot shall be as listed under the sublot size heading in the table above. If there is insufficient quantity in a lot to make up at least three sublots of the designated size in Table 3, then the lot quantity will be divided into three equal sublots.

If there is less than one half of a sublot remaining at the end, then it shall be combined with the previous sublot. If there is more than one half sublot remaining at the end, then it shall constitute the last sublot and shall be represented by test results.

3.13.4 Test Results. The Engineer may calculate pay factors and price adjustments at any time while a lot is being produced. This may be necessary for a partial estimate or to see if quality is falling to a point where immediate attention is required. Pay factors will be determined from all available acceptance tests for the lot being evaluated.

3.13.5 Reject Material.

3.13.5.1 Rejection by Contractor. The Contractor may, prior to sampling, elect to remove any defective material and replace it with new material at no expense to the State. Any such new material will be sampled, tested, and evaluated for acceptance.

3.13.5.2 An individual sublot. For any sublots with any test results exceeding the specified reject limits, the Engineer will:

1) Require complete removal and replacement with hot asphalt mix meeting the contract requirements at no additional expense to the department, or
2) Require corrective action to the satisfaction of the Engineer at no additional expense to the Department.

3.13.5.3 A lot in progress. The Contractor shall shut down paving operations whenever:

1) The pay factor for any property drops below 1.00 and the Contractor is taking no corrective action or
2) The pay factor for any property is less than 0.90 or
3) Two consecutive tests show that less than 50 percent by weight of the particles retained on the No. 4 sieve have at least one fractured face.

Paving operations shall not resume until the Engineer determines that material meeting the contract requirements can be produced. Corrective action will be considered acceptable by the Engineer if the pay factor for the failing property increases. If it is determined that the resumption of production involves a significant change to the production process, the current lot will be terminated and a new lot will begin.

3.14 Acceptance Testing

3.14.1 Gradation and Asphalt Cement Content. Samples for gradation and asphalt cement content shall be obtained from behind the paver by the Department in conformance to the procedure outlined below. The sample location will be established by selecting a random offset and station within each sublot in accordance with 106.

3.14.1.1 Sampling Procedure. For layers placed on an aggregate base, a 12 inch square aluminum plate will be laid down in the predetermined location before paving. Care shall be taken to mark the location of the plate so that it can be quickly found after the mix is placed. After the paver passes over the plate and before rolling occurs, the required amount of hot mix, as shown in Table 4, shall be scooped into transport containers using an aluminum flat bottomed scoop. On layers placed on new or existing pavement, the plate shall not be used. Where samples have been taken, new material shall be placed and compacted to conform to the surrounding area immediately after the samples are taken.

Table 4 - SAMPLE SIZE GUIDELINES

Base Courses	2000-3000 grams
Binder Courses	1500-2000 grams
Surface Courses	1000-1500 grams
Sand Courses	500-800 grams

3.14.1.2 Target values shall be as specified in the mix formula. All sieve sizes specified in the job mix formula will be evaluated for gradation. The specification limits in Table 5 will be used for calculating pay factors for gradation and asphalt cement content.

Table 5 - GRADATION AND ASPHALT CEMENT ACCEPTANCE LIMITS

PROPERTY	USL and LSL
Passing 1" and larger sieves	Target +/- 6.0 percent
Passing No. 4 to 3/4" sieves (inclusive)	Target +/- 4.0 percent
Passing No. 10 to No. 80 sieves (inclusive)	Target +/- 2.0 percent
Passing No. 200 sieve	Target +/- 1.0 percent
Asphalt Cement	Target +/- 0.30 percent

Any sublot with a gradation or asphalt cement content falling outside the ranges of the reject limits in Table 6 will be either removed and replaced at the expense of the Contractor or require corrective action to the satisfaction of the Engineer. After replacement, new samples will be taken and the old test results from that sublot will be discarded.

Table 6 - GRADATION AND ASPHALT CEMENT CONTENT REJECT LIMITS
(Deviation from Target)

	BASE COURSES			WEARING COURSES		
SIEVE SIZE	TYPE A: 1-1/4"	TYPE B: 3/4"	TYPE C: 1/2"	TYPE D: 3/4"	TYPE E: 1/2"	TYPE F: 3/8"
	PERCENT PASSING BY WEIGHT - COMBINED AGGREGATE					
1-1/4"	~~92-100~~					
1"	~~72-98~~±*12*					
3/4"	~~59-87~~*(1)*	~~92-100~~*(1)*		~~92-100~~*(1)*		
1/2"	~~47-73~~*(1)*	~~67-95~~±*10*	~~92-100~~*(1)*	~~79-100~~±*9*	~~92-100~~*(1)*	
3/8"	~~39-63~~*(1)*	~~57-83~~*(1)*	~~62-88~~±*10*	~~65-93~~*(1)*	~~82-98~~±*10*	~~92-100~~*(1)*
No. 4	~~25-48~~±*9*	~~39-60~~±*9*	~~35-53~~±*9*	~~47-82~~±*9*	~~55-78~~±*9*	~~61-83~~±*9*
No. 10	~~16-29~~±*7*	~~26-40~~±*7*	~~26-38~~±*7*	~~34-69~~±*7*	~~36-52~~±*7*	~~42-57~~±*7*
No. 20	~~8-20~~±*6*	~~14-26~~±*6*	~~14-26~~±*6*		~~22-34~~±*6*	~~23-37~~±*6*
No. 40	~~3-15~~*(1)*	~~7-19~~*(1)*	~~7-19~~*(1)*	~~15-46~~*(1)*	~~12-25~~*(1)*	~~13-27~~*(1)*
No. 80	~~0-11~~*(1)*	~~1-13~~*(1)*	~~1-13~~*(1)*	~~7-31~~*(1)*	4-~~16~~*(1)*	4-~~18~~*(1)*
No. 200	~~0-5~~±*3*	~~0-5~~±*3*	~~0-5~~±*3*	~~2-9~~±*3*	~~1-7~~±*3*	~~1-7~~±*3*
Asphalt Cement: % of Mix ~~(3)~~	~~3.7-4.9~~±*0.5*	~~7-6.1~~±*0.5*	~~4.9-5.9~~±*0.5*	~~5.4-6.6~~±*0.5*	~~5.6-7.1~~±*0.5*	~~5.8-7.1~~±*0.5*

(1) Reject limits will be waived for these sieves.

3.14.2 Air Voids. Air voids shall be determined by 6 inch diameter cores taken on each pavement layer by the Contractor in the presence of the Engineer. Full depth cores containing all new pavement layers will be required when sampling the wearing surface layer, for purpose of total thickness determination. Core locations will be established by selecting a random offset and station within each sublot in accordance with 106 except in the following locations:

a) Within 1 foot from an edge of pavement to be left unconfined upon project completion.
b) Within 4 feet from any drainage structure.
c) Within shoulders 4 feet or less in width.
d) Within 1 foot from shoulders 4 feet or less in width, placed on the same pass as the shoulder.

The Contractor shall deliver the core samples with complete identification information to the Engineer for testing by the Department. Identification shall include:

a) Project name & number.
b) Date sampled.
c) Location in station and offset.
d) Lot and sublot number.
e) Plan thickness.

Core sampling shall be in conformance to AASHTO T- 230. Cores shall be taken before opening pavement to traffic, except when location of core is within the last hour of that days placement. Cores shall be taken no within 24 hours after placement. Where cores have been taken, new material shall be placed and compacted to conform to the surrounding area the same day the samples are taken. Cores shall be protected against damage and delivered to the Department as quickly as possible. The specification limits in Table 7 will be used for calculating pay factors for air voids:

Table 7 - AIR VOIDS ACCEPTANCE LIMITS

	TARGET	LSL	USL
Air Voids in Total Mix	7.0 percent	5 percent	9 percent

3.14.2.1 Maximum Theoretical Density (MTD). ~~Samples shall be taken once per sublot behind the paver at the same time and location that the sample for gradation and asphalt content are taken. MTD will be compared against the core representing the same sublot for void determination.~~ *MTD shall be determined once per sublot from the core obtained for determining air voids.*

3.14.3 Pavement thickness. The thickness requirements contained herein shall apply only when each pavement layer is specified to be a uniform thickness greater than 3/4 inch. The combined total thickness of the hot asphalt mix or mixes will be measured to determine compliance with the acceptance tolerances in Table 8. Measurements shall be obtained from cores removed from the pavement after the placement of the wearing surface. Cores shall include all new layers placed.

Table 8 - THICKNESS ACCEPTANCE TOLERANCES

SPECIFIED COMBINED THICKNESS	ALLOWABLE TOLERANCE
3/4" to 2"	+/- 1/4"
2 1/2" to 4 1/2"	+/- 3/8"
5" to 7"	+/- 1/2"
7 1/2" and over	+/- 5/8"

Once each combined thickness measurement has been taken, a thickness index will be calculated. The thickness index is the actual deviation from target divided by the allowable tolerance in Table 8. This will allow statistical comparisons to be made among measurements based on varying specified thickness. Thickness indexes will be established for the sole purpose of calculating pay factors. Thickness index shall be calculated under the following equation using the specification limits in Table 9.

$$TI = \frac{(M - ST)}{T}$$

where: TI = Thickness Index
ST = Specified Thickness
M = Core Measurement
T = Allowable Tolerance

Table 9 - THICKNESS INDEX ACCEPTANCE LIMITS

	TARGET	LSL	USL
Thickness Index	0	-1	+1

14.4 Asphalt Cement Viscosity. Asphalt cement viscosity will be evaluated by comparison of the actual viscosity value with the specified viscosity limits at 140 degrees Fahrenheit. Specified viscosities and tolerances for each grade of asphalt cement are listed in Table 10. *Samples will be taken from the line by contractors personnel at the direction of Department~~Dept~~ personnel and shall be taken within 1 hour of the roadway sample for that sublot.*

3.14.4.1 The Contractor shall provide in the asphalt cement feed lines connecting the plant storage tanks to the weighing system, a sampling outlet consisting of a valve installed in such a manner that samples may be withdrawn from the line slowly at any time during plant operation. The sampling outlet shall be installed between the pump and the return discharge line in such a location that it is readily accessible and free from obstruction. A drainage receptacle shall be provided for flushing the outlet prior to sampling.

Table 10 - ASPHALT CEMENT VISCOSITY ACCEPTANCE LIMITS (poises)

	AC-2.5	AC-5	AC-10	AC-20	AC-30	AC-40
Target	250	500	1000	2000	3000	4000
Accept	200-300	400-600	800-1200	1600-2400	2400-3600	3200-4800
Reject	<50 and >350	<350 and >700	<700 and >1400	<1400 and >2400	<2400 and >3600	<3200 and >4800

If the viscosity value is within the accept limits for the specified asphalt grade, the asphalt cement will be accepted as being in conformance and no pay adjustment will apply.

If the viscosity value is outside the accept limits and within the reject limits, the Engineer may:

1) Require corrective action at no additional expense to the Department; or
2) Accept the asphalt cement with a calculated price adjustment as described in 5.4.2.

3.14.5 Ride Smoothness.

3.14.5.1 The Contractor shall furnish and have available a ten foot, light weight metal straightedge with a rectangular cross section of 2" x 4" at the paver at all times during paving operations. All courses shall be tested with the straightedge laid parallel to the center line and any variations from a true profile exceeding 3/16 of an inch shall be satisfactorily eliminated. The finished surface of the pavement shall be uniform in appearance, free from irregularities in contour and shall present a smooth-riding surface.

3.14.5.2 A GM type profilometer will be furnished by the Department for determination of pavement smoothness. This device produces a Ride Number for the surface tested. The surface will be tested within 30 days after completion of wearing surface over the entire project.~~ Testing shall include all mainline paving including bridges, plus ramps and lanes at least 11 feet wide. Testing will begin 25 feet before the approach joint and end 25 feet after the departure joint. Smoothness testing will be waived on tapers and sections less than 0.1 mile in lane length.~~ Immediately before testing, the Contractor will insure the surface is entirely free from any foreign matter that may affect the test results. No special considerations will be given to criteria such as degree of curve and vertical geometry. Ride Number will be calculated to the nearest one hundredth for each 0.1 mile segment.

3.14.5.3 Profilometer testing will include all mainline paving including bridges, ramps, and lanes at least 11 feet wide. Testing will begin 20 feet after the approach joint and end 20 feet before the departure joint. The pavement will not be evaluated over bridge expansion joints, tapers, and sections less than 0.1 mile in lane length.

3.14.5.3*4* All areas with bumps or high points exceeding 0.3 inches in 25 feet shall be corrected by removal of a minimum of 1 inch of the full lane width by the length required (a minimum of 100 feet) and replace~~mented~~*ed* at the Contractor's expense.

3.14.5.4*5* Ride Smoothness will be evaluated against the ride smoothness limits in Table 11.

Table 11 - RIDE SMOOTHNESS TESTING LIMITS

TYPE OF CONSTRUCTION	TARGET	LSL
Full depth construction/partial depth cold planning and paving	Ride Number of 4.3	4.0

3.14.5.5*6* Full depth construction shall include placing new subbase material and all new pavement courses. A final Ride Number shall be established after the wearing surface is complete. Any sublot with a ride number less than 3.5 shall be removed and replaced.

3.14.6 Cross Slope.

3.14.6.1 Cross slope will be measured once per sublot *(one test per 500' per lane)* after final rolling of the wearing surface has taken place. Only travel lanes will be evaluated for cross slope. The procedure for measuring the cross slope shall be by placing a 10 foot metal straight edge on the surface perpendicular to the traveled lane. The straight edge shall be held level by placing a 4 foot level on top of it. One end of the straight edge will rest on the pavement on the high end of the cross slope and a measurement will be taken on the other end of the straight edge and recorded to the nearest hundredth of a foot. From this measurement the percentage of cross slope shall be calculated to the nearest tenth of a percent.

3.14.6.2 Once a cross slope percentage has been measured, a cross slope index (CSI) will be calculated. The target cross slope shall be defined as the cross slope shown on the plans or as ordered to the nearest tenth of a percent. The CSI is the actual deviation from the target divided by the allowable tolerance of 0.5 percent. This will allow statistical comparisons to be made among measurements based on varying specified cross slopes. The CSI will be established for the sole purpose of calculating pay factors. The CSI shall be calculated under the following equation using the specification limits in Table 12.

$$CSI = \frac{(M - SCS)}{0.05}$$

where: CSI = Cross Slope Index
SCS = Specified Cross Slope in percent
M = Measured Cross Slope in percent

Table 12 - CROSS SLOPE INDEX ACCEPTANCE LIMITS

	TARGET	LSL	USL
Cross Slope Index	0	-1	+1

3.14.6.3 Cross slope will only be evaluated when specific slopes and superelevations are shown on the plans.

<u>Amend</u> 4.1 to read:

4.1 Asphalt pavement will be measured by the ton to the nearest 0.1 of a ton, and in accordance with 109.01. Batch weights will be permitted as a method of measurement only when the provisions of 3.4.3 are met, in which case, payment will be based on the cumulative weight of all the batches. The tonnage shall be the weight used in the accepted pavement and no deduction will be made for the weight of asphalt cement or additives in the mixture.

<u>Amend</u> 4.2 to read:

4.2 Asphalt pavement, removed because of faulty workmanship or contamination by foreign materials, will not be included in the pay tonnage.

<u>Add</u> to Basis of Payment:

5.4 Implementation of the Quality Control Plan and costs associated with obtaining core samples for acceptance testing shall be subsidiary. When items are to be accepted under Quality Assurance provisions, pay adjustment will be made in accordance with 106.03.2.4 as specified below.

5.4.1 Composite pay factor (CPF). The total price for each lot will be adjusted by a composite pay factor (CPF) based on the properties of gradation, asphalt content, and air voids. Evaluation will be made using the price adjustment factors in Table 12 in equation 9, under 106.03.

Table 13 - PRICE ADJUSTMENT FACTORS

PROPERTY		"f" FACTOR
Gradation (each sieve)	#10, #40 and #200 sieves	8
	All other sieves (each)	2
Asphalt Content		40
Air Voids		50

The price adjustment will be determined as follows:

$$PA = (CPF - 1)(Q)(P)(0.40)$$

where: PA = Price adjustment payment in dollars.
CPF = Composite pay factor with respect to the test properties listed above
Q = Quantity represented by CPF in tons.
P = Contract unit price per ton.
0.40 = Weight given to the composite price adjustment.

Composite price adjustments shall be applied to item 51.400. Price adjustments may be applied at the end of each month based on all available test results for each lot.

5.4.2 Pavement Thickness. The price adjustment for pavement thickness per lot made up of the sum of all sublots, used for calculating the composite pay factor above will be determined as follows:

$$PA = (PF - 1)(Q)(P)(0.10)$$

where: PA = Price adjustment payment in dollars.
PF = Pay factor based on statistical analysis on all thickness test results
Q = Quantity represented by all lots on the project.
P = Contract unit price per ton.
0.10 = Weight given to pavement thickness price adjustment.

Price adjustments for pavement thickness shall be applied to item 51.400. Price adjustments may be applied at the end of each month based on all available test results for each lot.

5.4.3 Asphalt cement viscosity. Price adjustments for asphalt cement with non-conforming viscosity values represented by an acceptance test per two tanker loads will be subject to the following pay adjustment:

$$PA = -0.0005\ VS - VA\ (Q)(P)$$

where: PA = Price adjustment payment in dollars.
VS = Specified viscosity target for specified asphalt grade.
VA = Actual viscosity failing test result.
Q = Quantity represented by previous two tanker load in tons.
P = Monthly sales price as determined in item 50.01.

Asphalt cement price adjustment shall be applied to item 50.01. Price adjustments may be applied at the end of each month based on all failing test results for that month.

5.4.4 Ride Smoothness. The price adjustment for ride smoothness per lot will be determined as follows:

$$PA = (PF - 1)(Q)(P)(0.30)$$

where: PA = Price adjustment payment in dollars.
PF = Pay factor based on statistical analysis on all sublots.
Q = Quantity of the sum of all lots in tons.
P = Contract unit price per ton.
0.30 = Weight given to quality of ride smoothness price adjustment.

Price adjustments for ride smoothness shall be applied to item 51.401. Price adjustments may be applied at the end of each month based on all available test results for each lot.

5.4.5 Cross Slope. The price adjustment for cross slope per lot will be determined as follows:

$$PA = (PF - 1)(Q)(P)(0.20)$$

where PA = Price adjustment payment in dollars.
PF = Pay factor based on statistical analysis on all cross slope measurements.
Q = Quantity represented by all lots on the project.
P = Contract unit price per ton.
0.20 = Weight given to pavement cross slope price adjustment.

5.4.5.1 Negative price adjustments for cross slope will not be applied to this project.

5.4.6 Negative price adjustments will be assessed. *and all negative pay adjustments will be multiplied by the factor shown in T*able 14. All provisions of 3.13.5 shall apply.

TABLE 14

YEAR CONTRACT AWARDED	FACTOR FOR NEGATIVE PAY ADJUSTMENT
1997	0.25
1998	0.50
1999	0.75
2000	1.00

Add to Pay items and units:

403.XXXX2	Hot Bituminous Pavement, ________ ____________________ (QC/QA)	Ton
404.XXXX2	Recycled Hot Bituminous Pavement (QC/QA)	Ton
51.400	Price Adjustment for Quality of Hot Bituminous Pavement[1]	Dollar
51.401	Price Adjustment for Quality of Ride Smoothness[1]	Dollar

[1]Not a bid item

Vermont Agency of Transportation

RQ SPECIFICATION
Vermont Agency of Transportation

BOLTON-SOUTH BURLINGTON I-89 IM089-2(24) SOUTHBOUND
MM 71.600 to 86.929 Length 15.329

406.16 **SURFACE TOLERANCE-** - ACCEPTANCE TESTING OF THE SURFACE WILL BE PERFORMED ONLY ON THE WEARING COURSE. THE SURFACE ROUGHNESS WILL BE MEASURED BY THE ENGINEER, OR HIS REPRESENTATIVE WITH A AGENCY OWNED TRAILER MOUNTED RAINHART MAYS RIDE METER AFTER ALL THE PAVEMENT HAS BEEN PLACED. SURFACE OBSTRUCTIONS WILL BE ELIMINATED FROM THE FINAL PROJECT AVERAGE, SUCH AS BRIDGES THAT REMAINED UNPAVED WITHIN THE PROJECT LIMITS. TESTING WILL BE PERFORMED WITHIN TWO WEEKS OF THE PERMANENT MARKING PLACEMENT.

FINAL PAY FACTOR FOR ALL OPEN GRADED FRICTION COURSE WILL BE ADJUSTED BY THOSE FACTORS SHOWN IN TABLE 406.16A, BASED ON THE AVERAGE OF THREE RUNS OF MEASURED ROUGHNESS AT THE POSTED SPEED LIMIT FOR THE TRAVEL AND PASSING LANES THEN AVERAGED TO ARRIVE AT THE FINAL PROJECT AVERAGE.

TABLE 406.16A

PAY FACTOR	ROUGHNESS INDICATED IN IRI
1.10	< 49
1.05	50 - 59
1.00	60 - 69
.98	70 - 82
.95	83 - 95
.90	> 96

THE TOTAL TONNAGE OF OPEN GRADED FRICTION COURSE ALREADY ADJUSTED BY ANY APPLICABLE PAY FACTORS WILL BE MULTIPLIED BY THE FINAL PAY FACTOR IN TABLE 406.16A, TO DETERMINE THE ACCEPTED QUANTITY TO BE PAID.

RQ Specifications Currently Used in Other States

Arizona Department of Transportation

RQ SPECIFICATION

Arizona Department of Transportation

SCOPE

1. This test method describes a procedure for measuring the smoothness of pavements. Smoothness measurements are taken at 0.1 mile increments, or a portion thereof, on the designated area(s) of the pavement. Measurements are reported as Mays-Meter inches per mile (in/mi).

APPARATUS

2. The equipment used shall be one of the following:

(a) General Motors Research (GMR)-type Profilometer.

(b) Mays-Meter, that has been correlated at 50 mph, to a GMR-type Profilometer.

METHOD OF MEASURING

3. (a) The measuring device is driven over the area(s) to be tested and measurements are taken for each 0.1 mile increment.

(b) Three measurements for each 0.1 mile increment are obtained.

(c) The measuring speed for the GMR-type Profilometer will be a constant speed ± 2 mph, between 30 and 50 mph.

(d) The measuring speed for the Mays-Meter will be 50 ± 2 mph.

CALCULATIONS

4. (a) GMR-type Profilometer measurements will be reduced to Mays-Meter values (inches per mile) using the model defined in NCHRP Report #228, "Calibration of Response-Type Road Roughness Measuring Systems", and illustrated on page 25, Figure 22, of that report.

NOTE: NCHRP Report #228 is available from the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C., 20418. It may also be ordered from them by phone at (202)334-3214.

(b) Raw Mays-Meter measurements will be reduced to equivalent GMR-type Profilometer Mays-Meter values through a correlation equation (50 mph) relating the Mays-Meter used to a GMR-type Profilometer. The correlation equation shall have a correlation coefficient (r) of 0.92 or higher.

(c) The three individual measurements for each 0.1 mile increment are averaged and the result recorded to the nearest 0.1 in/mi.

REPORT

5. A report will be prepared showing:

(a) The date of test.

(b) The name of the test operator(s).

(c) Identification of test vehicle.

(d) Project Number, if applicable.

(e) The location of each 0.1 mile increment tested.

(f) The three individual measurements, in Mays-Meter inches per mile, for each 0.1 mile increment.

(g) The average of the three individual measurements, in Mays-Meter inches per mile, for each 0.1 mile increment.

Kansas Department of Transportation

RQ SPECIFICATION

Kansas Department of Transportation

STANDARD SPECIFICATIONS
EDITION OF 1990
METRIC VERSION

DIVISION 600

FLEXIBLE PAVEMENT
(Pavement Trueness)

PAVEMENT TRUENESS

(a) General.

(1) The Contractor shall determine the smoothness of pavement by operating a profilograph over the finished surface of the mainline pavement, sideroads, auxiliary lanes and ramps.

(2) All bituminous roadways receiving 100 mm or greater in Plan thickness of virgin and/or hot recycled bituminous pavement are subject to this specification.

(3) The following bituminous roadways must be profiled and corrected as necessary to meet these specifications; however, these roadways are not subject to pay adjustments.

(3.1) Existing roadways that are milled, then surfaced with less than 100 mm of virgin and/or hot recycled bituminous pavement.

(3.2) Existing roadways that are surfaced with less than 100 mm of virgin and/or hot recycled bituminous pavement which is placed in two or more lifts.

(3.3) Existing roadways that are cold recycled, then surfaced with less than 100 mm of virgin and/or hot recycled bituminous pavement.

(4) The following surfaces are specifically excluded from the terms of this special provision:

(4.1) Bridge decks unless to be overlaid;

(4.2) Acceleration and deceleration lanes for at grade intersections;

(4.3) Side roads less than one section (100 m) in length;

(4.4) Shoulders;

(4.5) Pavement on horizontal curves which have a 300 m or less centerline radius of curvature and pavement within the superelevation transition of curves;

(4.6) County secondary; and federal aid urban projects with posted speeds 40 mph or less, unless specified otherwise on the Plans;

(4.7) Projects less than one-half kilometer in length (excluding bridge lengths).

(4.8) Existing roadways that are surfaced with less than 100 mm of virgin and/or hot recycled bituminous pavement which is placed in one lift.

(5) On bituminous concrete pavement surfaces not subject to profilograph testing, the surface will be tested with a straightedge or string line in accordance with subsection 603.03(e)(6) of the Standard Specifications.

(b) Equipment.

The pavement profile shall be determined using a California type profilograph or other style of machine that yields compatible results and has been approved for use by the Bureau of Materials and Research. The equipment shall be furnished and operated by the Contractor in accordance with the requirements of KT-54-95 (Kansas Test Method for Determination of Pavement Profile with the Profilograph).

(c) Surface Test.

Pavement profile testing will be required only on the final surface of the pavement. The testing shall be performed by a Department certified profilograph operator in accordance with the procedures for one lane paving operations shown in KT-54-95 and two traces shall be made for each lane. The traces shall be made after final rolling and before the surface is opened to traffic; except, the Contractor has the option of profiling the final portion (not to exceed five sections) of a day's production the first working day that production is continued in the same lane. If the Contractor elects to test intermediate lifts with the profilograph, the profilograms shall be made available to the Engineer to review for the purposes of evaluating the paving methods and equipment.

A profilogram shall be made for each continuous placement of 15 meters or more of the final surface lift. The profilogram shall include the five meters at the ends of the placement only when the Contractor is responsible for the adjoining surfaces.

Individual surface placements shorter than 15 meters will be inspected and tested with a straightedge or string line by the Engineer in accordance with subsection 603.03(e)(6) of the Standard Specifications. The five meters at the ends of longer placements will also be inspected in this manner when excluded from the profilogram.

(d) Smoothness Evaluation.

(1) The evaluation of the profilograph traces shall be performed by a Department certified profilograph operator and the evaluation report shall be certified by the operator. The evaluation of the trace shall be performed in accordance with the procedures of KT-54-95.

(2) A profile index in millimeters per kilometer shall be determined from the profilogram that represents each section or portion thereof, of the finished pavement surface. A section of pavement shall be defined as a continuous area of pavement 0.1 kilometer (100 m) in length and one lane (3.7 m nominal) in width. Portions of sections that result from interruptions of the continuous pavement surface (i.e. bridge approaches, sideroad tie-ins, the cessation of the daily paving operations, etc.) shall be subject to all requirements stated in this special provision for a section.

A daily average profile index shall also be determined for the surface of each day's placement of the final surface lift. If the average profile index exceeds 630 mm/km per lane for any single day's production, the paving operation will be suspended and paving shall not resume until corrective action is taken by the Contractor. For the purposes of determining a day's production the following shall apply:

(2.1) A days production is defined as the placement of a minimum of one section of pavement in a day.

(2.2) If less than one section is paved, that day's production will be grouped with the next day's production.

(2.3) If the production of the last day of project paving is less than one section it will be grouped with the previous day's production.

(2.4) If the Contractor opts to profilograph the final portion of a day's production (as described in subsection (c)) the first working day that production is continued in the same lane, the final portion of the previous day's production will be grouped with the day's production as the lane is continued.

(3) The Contractor shall furnish the surface profilograms and his evaluations to the Engineer the first working day following placement of the pavement represented by the profilograms.

(e) Corrective Actions.

(1) Each section of pavement will be evaluated using the profilograph to determine if corrective actions are necessary. Each individual profilogram trace will be evaluated (not the average of multiple traces) to determine areas where corrective action is needed.

All areas within each section having high points (bumps) with deviations in excess of ten millimeters in a length of 7.5 meters or less shall be corrected regardless of the profile index value.

(2) Pavement surfaces having an initial profile index greater than 475 mm/km per section on an individual trace shall be corrected to reduce the profile index to 475 mm/km or less per section for that trace.

(3) As an exception to (e)(2), ramps, from the nose to the intersection of the adjoining roadway, and acceleration and deceleration lanes including the taper (acceleration lanes that become a through lane are limited to 150 m from the nose) having an initial profile index greater than 630 mm/km per section on an individual trace shall be corrected to reduce the profile index to 630 mm/km or less per section for that trace.

(4) When profile corrections are required, the Contractor shall use one or more of the following corrective methods:

(4.1) Diamond grinding or use of other profiling devices;

(4.2) Removing and replacing the entire pavement thickness;

(4.3) Removing the surface by milling and applying a lift(s) of the specified surface course;

(4.4) Overlaying (not patching) with the specified surface course;

(4.5) Use of other methods that will provide the desired results;

The corrective method(s) chosen by the Contractor shall be subject to the approval of the Engineer and shall be performed at the Contractor's expense. The Contractor shall retest any section where corrections were made to verify that the corrections have produced a profile index of 475 mm/km (630 mm/km for areas specified in (e)(3)) or less per section for each trace. The Contractor shall furnish the surface profilogram and his evaluation to the Engineer within two working days after any corrections are made.

The Engineer may perform profilograph testing on the surface for monitoring and comparison purposes. If it is determined that the Contractor's certified test results are inaccurate, the Engineer may choose to test the entire project length and the Contractor will be charged for such testing at a rate of $400.00 per kilometer per profile track with a minimum charge of $800.00. Furthermore, furnishing inaccurate test results may result in decertification of the Contractor's certified operator.

(f) Pay Adjustments.

Pay adjustments will be based on the initial average profile index determined for the 0.1 km section prior to performing any corrective work except that; if the Contractor chooses corrective methods 4.2, 4.3 or 4.4 listed above in (e), then the Contractor will be paid the contract price plus or minus the price that corresponds to the initial average profile index obtained on the pavement section after replacement. Areas excluded from pay adjustments under (a)(3) and areas excluded from the profilograph testing under (a)(4) will not be subject to price adjustments.

When the initial average profile index of a 0.1 km section s 160 mm/km or less, payment will be increased by the ppropriate amount as shown in TABLE 1. When the initial average rofile index of a 0.1 km section is between 161 mm/km and 630 m/km, no adjustments in payment will be made. When the initial verage profile index of a 0.1 km section is greater than 476 n/km (greater than 631 mm/km for areas specified in (e)(3)), orrective action is required, and payment will be in accordance ith TABLE 1, SCHEDULE OF ADJUSTED PAYMENT.

TABLE 1
SCHEDULE FOR ADJUSTED PAYMENT

'erage Profile Index m/km per lane)	Contract Price Adjustment Per 0.1 Lane km (Dollars)
0 or less	+100.00
1 to 160	+ 50.00
1 to 475	0.00
.6 to 630	0.00 (Correct to 475 mm/km)
1 or more	-120.00 (Correct to 475 mm/km)

Payments made for "Bituminous Pavement Smoothness" will shown as an added item to the Contract.

·14-95 M&R(RU) (WHP)

Michigan Department of Transportation

RQ SPECIFICATION
Michigan Department of Transportation

a. Description

This specification is to provide an incentive for contractors to construct the smoothest riding pavements possible. This specification provides two methods of measuring the ride quality of concrete and bituminous pavements. The contractor has the option of using either method. Once a method has been selected by the Contractor, it may not be changed without authorization from the Engineer. The ride quality of bituminous pavements having multiple courses will have the ride quality determined for both the topmost leveling and the wearing course. This Special Provision deletes paragraph five of Section 4.00.03-d, Section 4.00.12, and Section 4.50.13 paragraphs two, three, and four of the 1990 Standard Specifications.

b. Methods of Determining Pavement Smoothness

1. Using the California Type Profilograph

Ride quality of the pavement, expressed in inches per mile, will be determined from a mechanically produced profilogram (trace) or from a computerized version of the California type profilograph. Pavement lanes constructed with 0 to less than 4 inches per mile will result in payment of varying percentages based on Table 1. Lanes with 4 to 10 inches per mile will not be eligible for any bonus payments for ride quality. Lanes with more than 10 inches per mile will not be acceptable. All areas with bumps or high points exceeding 3/10 of an inch in 25 feet will be corrected to remove the high point. All pavements shall be corrected to achieve a value of 10 inches per mile or less at no cost to the Department.

2. Using the GM Type Rapid Travel Profilometer

Ride quality of the pavement, expressed as RQI (Ride Quality Index) units, or inches per mile will be determined by proper reduction of the true profile obtained by a GM Type of Rapid Travel Profilometer. The contractor has the option of using either unit of measurement. Once the unit of measurement has been chosen by the contractor, it may not be changed without authorization from the Engineer. Pavement lanes constructed with an RQI from 22 to 45 will result in payment of varying percentages based on Table 2. Lanes with RQIs of 45 to 53 will not be eligible for any bonus payments for ride quality. Pavement lanes with a RQI more than 53 are not acceptable. All pavement lanes shall be corrected to achieve an RQI value of 53 or less at no cost to the Department. Pavement lanes constructed with 0 to less than 4 inches per mile will result in payment of varying percentages based on Table 1. Lanes with 4 to 10 inches per mile will not be eligible for any bonus payments for ride quality. Lanes with more than 10 inches per mile will not be acceptable. All pavements shall be corrected to achieve a value of 10 inches per mile or less at no cost to the Department.

All areas with bumps or high points exceeding 3/10 of an inch in 25 feet shall be corrected to remove the high point.

c. Equipment. The contractor shall certify, in writing, that the equipment used is in compliance with this special provision.

1. California Type Profilograph

The contractor shall furnish a California type profilograph, which is either mechanical or computerized, and trained operators who shall operate the profilograph. The profilograph shall produce a profilogram with a true 1 to 1 vertical scale and a true 1 inch to 25 feet horizontal scaling. The profilogram shall have roadway stations recorded thereon.

2. GM Type Rapid Travel Profilometer

The contractor shall furnish a profilometer based on the General Motors Rapid Travel concept. The unit shall produce a true profile for spatial wavelengths from 2 to 110 feet. The unit must also be able to generate the equivalent California Profilograph plot and inches per mile values as well as locations of bumps over 3/10 inch in 25 feet. The unit shall also be capable of producing a plot of the true profile with a range from 2 to 110 foot wavelengths.

d. Equipment Design Requirements

1. Computerized California Type Profilograph

If the profilograph is equipped with an on-board computer, the following conditions shall apply: Vertical displacement shall be sampled every 3 inches or less along the roadway. The profile data shall be bandpass filtered in the computer to remove all spatial wavelengths shorter than 2 feet and longer than 110 feet. This shall be accomplished by a third order, low pass Butterworth filter set at 2 feet and a third order, high pass Butterworth filter set at 110 feet. The resulting band limited profile will then be computer analyzed according to the California Profilograph reduction process to produce the required inches per mile statistic. This shall be accomplished by fitting a linear regression line to each 528 feet of contiguous pavement section. This corresponds to the perfect placement of the blanking bar by a human trace reducer. Scallops are then detected and totalized according to the California protocol. Bump analysis shall take place according to the California Profilograph reduction process.

The computerized profilograph shall produce a plot of the profile and a printout which will give the following data: Stations every 100 feet, bump height and bump length of specification (3/10 of an inch and 25 feet respectively), the blanking band width, date of measurement, total ride index in inches per mile for the measurement, total length of the measurement, and the raw inches for each tenth mile segment.

2. GM Type Rapid Travel Profilometer

The digitized profile shall be processed by dividing it into three spatial wavelength bands by using third order Butterworth high and low pass filters. The three bands are 50 to 25 feet, 25 to 5 feet, and 5 to 2 feet. Variance of the profile in each band is then computed:

$$Var_i = \frac{\Sigma x^2}{N} - \left(\frac{\Sigma x}{N}\right)^2$$

Where x is a profile elevation value in inches and N is the number of x values.

i = 1 for 50-25 feet, i = 2 for 25-5 feet and i = 3 for 5-2 feet.

RQI is then given by the formula:

$$RQI = 3.077 \ln (Var_1 \times 10^6) + 6.154 \ln (Var_2 \times 10^6)$$
$$+ 9.231 \ln (Var_3 \times 10^6) - 141.85$$

This provides a scale from 0 (a perfect road) to 100 (the roughest road).

This equipment shall give a printout of the same information as the profilograph with the addition of the ride quality index for each tenth of a mile segment and for the total run.

e. Calibration

1. California Type Profilograph

Each profilograph shall be calibrated and inspected at the project site at the beginning of each day it is used to measure pavement ride quality for specification compliance.

The calibration procedure for the mechanical machine shall consist of profiling two replicate runs on a designated roadway of 1,000 feet in length while observed by Department personnel. Horizontal calibration will be checked by running the profilograph over the 1,000 foot length and measuring the length of the resulting output on the profilogram. A 1,000 foot run must produce 40 inches (±1/8 inch) of profilogram output. Vertical calibration will be checked by running the test wheel over a block of known thickness (usually 1 inch) and measuring the displacement it produces on the profilogram. There will be no visible tolerance allowed on the vertical calibration.

Calibration of the computerized versions shall have a run made over a distance of a measured 2/10 of a mile (1,056 lft). The computer must print out a distance equal to the measured distance ± 5 ft. The vertical calibration will be as per the manufacturer's procedure and shall have no deviation.

If the horizontal or vertical checks do not meet specifications, the machinery must be corrected. In addition to the calibration procedures, a visual inspection of the profilograph must be conducted. This would include condition of the test tire and bogey wheels, tire pressure (25 psi ±1 psi), tracking of the paper on the spool and paper drum, condition of chains and cables, tracking of the device down the road, and general condition of the test device. This calibration procedure is the same for either type of profilograph.

2. GM Type Rapid Travel Profilometer

These devices can be tested for overall operation by performing the "Bounce" test procedure included with the unit. Horizontal measurement shall be checked over a measured distance of 2/10 of a mile (1,056 lft) and shall read within ± 5 feet of the measured distance. Vertical measurement shall be checked by passing the sensing device over a block of known thickness block with no deviation.

f. Method of Testing

The Engineer will establish and mark the limits for Ride Quality Measurement including the POB, POE, and any excluded area.

The Contractor shall make all corrections to the pavement and notify the Engineer a minimum of 24 hours prior to the official run for determination of ride quality.

The run will not be considered an official run until the pavement profile is in compliance with the requirements for this special provision.

The Contractor will be responsible for starting the California type profilometer with the measuring wheel on the mark, and ending on the mark at the end of the run. The GM type profilometer measurement should start 16.25 feet prior to the mark and end 16.25 feet after the mark at the end of the run. Profiles will be taken 3 feet from each side of each lane that is to be measured. Bridge decks will be excluded for payment of Ride Quality, but not for Ride Quality Measurement, by the operator. This requires software, mechanical or electronic means of suspending calculation of the ride quality statistic during passage over such sections, but retain linear measurement. All damage to the pavement surface caused by the profilometer shall be repaired at no increase in cost to the Department.

g. Method of Interpretation

1. Using the California Type Profilograph

The trace generated by the mechanical profilograph will be analyzed by the Engineer using a 2/10 of an inch blanking band measuring each deviation above and below the band to the nearest 5/100 of an inch according to Michigan Test Method MTM 204-88. Deviations will be summed for each 1/10 of a mile and proportional lengths as follows:

If less than 0.047 mile, include it in the previous 1/10 of a mile. If equal to or greater than 0.047 mile, let it stand as the next 1/10 of a mile. Each run will be reported by the contractor to the nearest 1/100 of an inch as the average inches per mile of the two runs for each lane.

If a computerized profilograph is used, the Engineer will not need to reduce the trace. A copy of the official computer generated trace and printout will be submitted for project records and to determine the ride quality payment.

2. Using the GM Type Rapid Travel Profilometer

RQI or In./Mi. will be calculated for each tenth of a mile segment. Partial segments will be treated as follows: If there is a partial segment at the beginning of an excluded section, it will be computed as a partial segment. If there is a partial segment at the end of an excluded section, it will be computed as a partial segment. If there is a partial segment at the end of a run, it will be computed as a partial segment. Each run will be reported to the nearest one tenth of a RQI unit (e.g., 48.6), or nearest five-hundredths of a (0.05) In./Mi. The contractor shall provide to the Engineer a trace and a printout which gives the same information as described for the profilograph.

h. Methods of Correction

1. Bituminous Pavements.-Corrections to leveling courses shall be by one of the following methods:

a. Diamond grinding.
b. Cold-milling.
c. Wedging of low points or areas.

Corrections to the wearing course shall be by:

a. Removal and replacement of a minimum of 1 and 1/4 inches of bituminous a full lane width by the length required (a minimum of 100 feet)
b. Diamond grinding.

Bumps which measure over 3/10 of an inch in 25 feet must be corrected by the method(s) specified above . All milling, wedging, and removal corrections shall be for a full lane width. All corrections are at the contractor's expense.

2. Concrete Pavements.-Bumps which measure over 3/10 of an inch in 25 feet must be corrected. Restoration of the transverse grooves in these areas will not be necessary provided that the grinding equipment establishes a grooved surface in the longitudinal direction. The contractor shall determine those areas which need correction. All corrections to concrete pavements shall be by diamond grinding and are at the contractor's expense.

3. Assessments.- Any tenth mile segments having an RQI over 53, or greater than 1.0 inch, will require correction at the contractor's expense.

i. Method of Measurement

The item of RIDE QUALITY MEASUREMENT will be measured as Lane Miles. The limits for Ride Quality Measurement will be based on 16.25 lineal feet before the POB and after the POE. (See Figure 1.)

Quantities for the item RIDE QUALITY - BITUMINOUS and RIDE QUALITY - CONCRETE will be determined by the area in square yards based on plan quantities or known changes. The limits for Ride Quality will be based on 16.25 lineal feet after the POB and before the POE. The limits for any excluded area will be 16.25 lineal feet before and after the section. Areas of ramps, tapers, bridge decks, and railroad crossings are not included under the item of Ride Quality. (See Figure 1.) Major intersections (at grade) with part width, maintained traffic, or staged construction will be considered as excluded areas. The excluded area will extend between the approach and departure spring points of the intersection.

Quantities for the item BUMP GRINDING will be determined by the area in square yards, outside the limits of RIDE QUALITY, as directed by the Engineer. See Figure 1.

j. Basis of Payment

Ride Quality Measurement-Bituminous . . . . . Lane Mile
Ride Quality Measurement-Concrete . . . . . . Lane Mile

Payment for the item RIDE QUALITY MEASUREMENT will include all costs of furnishing and operating the profilograph or rapid travel profilometer for the official run. If the Engineer requires ramps, tapers, approaches, or miscellaneous concrete pavement to be measured, they will be measured and paid for as Ride Quality Measurement.

No additional payment will be made for runs made by the contractor to determine the smoothness prior to corrections for the official runs.

Ride Quality-Bituminous . . . . Syd.
Ride Quality-Concrete . . . . Syd.
Bump Grinding . . . . Syd.

Payment shall be determined by the Engineer for the item RIDE QUALITY based on the inches per mile or RQI per mile for the final weighted average for all values within each lane. The limits for Ride Quality will be based on 16.25 lineal feet after the POB and before the POE and 16.25 lineal feet before and after any excluded area. Each lane will be determined individually.

Incentive for bituminous pavements will be paid at the contract unit price for Ride Quality for both the top course and the upper most leveling course. The criteria for making incentive payments or no payments for this item will be:

1. For the California Type Profilograph (Mechanical & Computerized)

   Incentive Payments.- A pavement lane having a range of 0 to 4 inches per mile will receive payments for Ride Quality based on the product of the number of square yards in the pavement lane (minus excluded areas) times the contract unit price for Ride Quality, multiplied by the appropriate pay factor from Table 1.

   No Payment.-A pavement lane having a range of 4 to 10 will not qualify nor receive any payment for Ride Quality.

2. For the GM Type Rapid Travel Profilometer

   Incentive Payments.-A pavement lane having an RQI range of 22 to 45, or a range of 0 to 4 inches per mile, will receive payments for Ride Quality based on the product of the number of lane miles in the pavement lane (minus excluded areas) times the contract unit price for Ride Quality, multiplied by the appropriate pay factor from Tables 1 or 2.

   No Payment.-A pavement lane having an RQI range of 45 to 53, or a range of 4 to 10 inches per mile, will not qualify nor receive any payment for Ride Quality.

Payment for the item, Bump Grinding will be used outside the limits of Ride Quality-Bituminous or Ride Quality-Concrete. These areas with bumps or high points exceeding 3/10 of an inch in 25 feet will be diamond ground as directed by the Engineer.

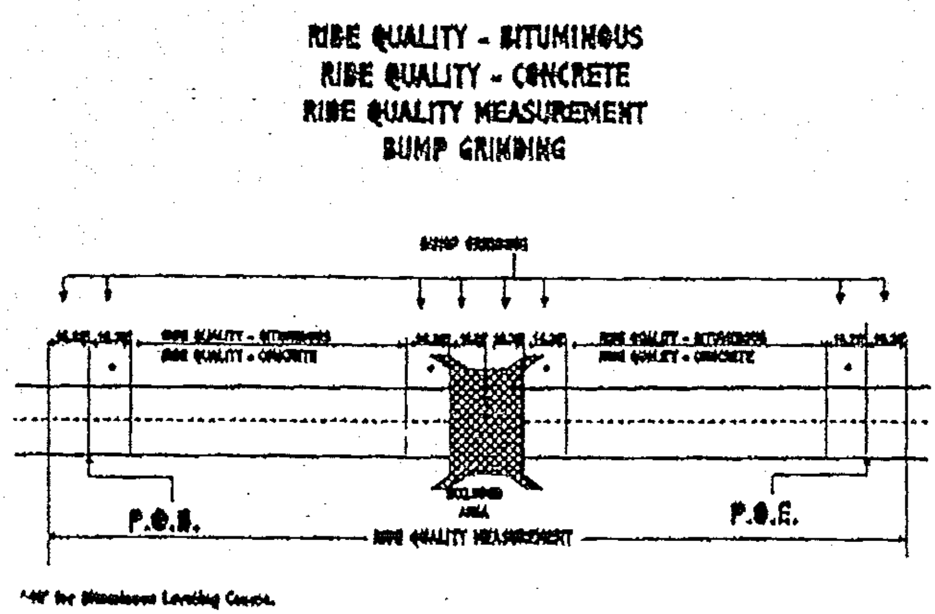


FIGURE 1

TABLE 1
PAY SCHEDULE FOR RIDE QUALITY USING PROFILE INDEX (Inches/Mile)
(FACTOR TO BE MULTIPLIED BY CONTRACT UNIT PRICE)

Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor
In./m	%	In./m	%	In./m	%	In./m	%	In./m	%	In./m	%	In./m	%	In./m	%	In./m	%
0.00	100.00	0.45	88.75	0.90	77.50	1.35	66.25	1.80	55.00	2.25	43.75	2.70	32.50	3.15	21.25	3.60	10.00
0.01	99.75	0.46	88.50	0.91	77.25	1.36	66.00	1.81	54.75	2.26	43.50	2.71	32.25	3.16	21.00	3.61	9.75
0.02	99.50	0.47	88.25	0.92	77.00	1.37	65.75	1.82	54.50	2.27	43.25	2.72	32.00	3.17	20.75	3.62	9.50
0.03	99.25	0.48	88.00	0.93	76.75	1.38	65.50	1.83	54.25	2.28	43.00	2.73	31.75	3.18	20.50	3.63	9.25
0.04	99.00	0.49	87.75	0.94	76.50	1.39	65.25	1.84	54.00	2.29	42.75	2.74	31.50	3.19	20.25	3.64	9.00
0.05	98.75	0.50	87.50	0.95	76.25	1.40	65.00	1.85	53.75	2.30	42.50	2.75	31.25	3.20	20.00	3.65	8.75
0.06	98.50	0.51	87.25	0.96	76.00	1.41	64.75	1.86	53.50	2.31	42.25	2.76	31.00	3.21	19.75	3.66	8.50
0.07	98.25	0.52	87.00	0.97	75.75	1.42	64.50	1.87	53.25	2.32	42.00	2.77	30.75	3.22	19.50	3.67	8.25
0.08	98.00	0.53	86.75	0.98	75.50	1.43	64.25	1.88	53.00	2.33	41.75	2.78	30.50	3.23	19.25	3.68	8.00
0.09	97.75	0.54	86.50	0.99	75.25	1.44	64.00	1.89	52.75	2.34	41.50	2.79	30.25	3.24	19.00	3.69	7.75
0.10	97.50	0.55	86.25	1.00	75.00	1.45	63.75	1.90	52.50	2.35	41.25	2.80	30.00	3.25	18.75	3.70	7.50
0.11	97.25	0.56	86.00	1.01	74.75	1.46	63.50	1.91	52.25	2.36	41.00	2.81	29.75	3.26	18.50	3.71	7.25
0.12	97.00	0.57	85.75	1.02	74.50	1.47	63.25	1.92	52.00	2.37	40.75	2.82	29.50	3.27	18.25	3.72	7.00
0.13	96.75	0.58	85.50	1.03	74.25	1.48	63.00	1.93	51.75	2.38	40.50	2.83	29.25	3.28	18.00	3.73	6.75
0.14	96.50	0.59	85.25	1.04	74.00	1.49	62.75	1.94	51.50	2.39	40.25	2.84	29.00	3.29	17.75	3.74	6.50
0.15	96.25	0.60	85.00	1.05	73.75	1.50	62.50	1.95	51.25	2.40	40.00	2.85	28.75	3.30	17.50	3.75	6.25
0.16	96.00	0.61	84.75	1.06	73.50	1.51	62.25	1.96	51.00	2.41	39.75	2.86	28.50	3.31	17.25	3.76	6.00
0.17	95.75	0.62	84.50	1.07	73.25	1.52	62.00	1.97	50.75	2.42	39.50	2.87	28.25	3.32	17.00	3.77	5.75
0.18	95.50	0.63	84.25	1.08	73.00	1.53	61.75	1.98	50.50	2.43	39.25	2.88	28.00	3.33	16.75	3.78	5.50
0.19	95.25	0.64	84.00	1.09	72.75	1.54	61.50	1.99	50.25	2.44	39.00	2.89	27.75	3.34	16.50	3.79	5.25
0.20	95.00	0.65	83.75	1.10	72.50	1.55	61.25	2.00	50.00	2.45	38.75	2.90	27.50	3.35	16.25	3.80	5.00
0.21	94.75	0.66	83.50	1.11	72.25	1.56	61.00	2.01	49.75	2.46	38.50	2.91	27.25	3.36	16.00	3.81	4.75
0.22	94.50	0.67	83.25	1.12	72.00	1.57	60.75	2.02	49.50	2.47	38.25	2.92	27.00	3.37	15.75	3.82	4.50
0.23	94.25	0.68	83.00	1.13	71.75	1.58	60.50	2.03	49.25	2.48	38.00	2.93	26.75	3.38	15.50	3.83	4.25
0.24	94.00	0.69	82.75	1.14	71.50	1.59	60.25	2.04	49.00	2.49	37.75	2.94	26.50	3.39	15.25	3.84	4.00
0.25	93.75	0.70	82.50	1.15	71.25	1.60	60.00	2.05	48.75	2.50	37.50	2.95	26.25	3.40	15.00	3.85	3.75
0.26	93.50	0.71	82.25	1.16	71.00	1.61	59.75	2.06	48.50	2.51	37.25	2.96	26.00	3.41	14.75	3.86	3.50
0.27	93.25	0.72	82.00	1.17	70.75	1.62	59.50	2.07	48.25	2.52	37.00	2.97	25.75	3.42	14.50	3.87	3.25
0.28	93.00	0.73	81.75	1.18	70.50	1.63	59.25	2.08	48.00	2.53	36.75	2.98	25.50	3.43	14.25	3.88	3.00
0.29	92.75	0.74	81.50	1.19	70.25	1.64	59.00	2.09	47.75	2.54	36.50	2.99	25.25	3.44	14.00	3.89	2.75
0.30	92.50	0.75	81.25	1.20	70.00	1.65	58.75	2.10	47.50	2.55	36.25	3.00	25.00	3.45	13.75	3.90	2.50
0.31	92.25	0.76	81.00	1.21	69.75	1.66	58.50	2.11	47.25	2.56	36.00	3.01	24.75	3.46	13.50	3.91	2.25
0.32	92.00	0.77	80.75	1.22	69.50	1.67	58.25	2.12	47.00	2.57	35.75	3.02	24.50	3.47	13.25	3.92	2.00
0.33	91.75	0.78	80.50	1.23	69.25	1.68	58.00	2.13	46.75	2.58	35.50	3.03	24.25	3.48	13.00	3.93	1.75
0.34	91.50	0.79	80.25	1.24	69.00	1.69	57.75	2.14	46.50	2.59	35.25	3.04	24.00	3.49	12.75	3.94	1.50
0.35	91.25	0.80	80.00	1.25	68.75	1.70	57.50	2.15	46.25	2.60	35.00	3.05	23.75	3.50	12.50	3.95	1.25
0.36	91.00	0.81	79.75	1.26	68.50	1.71	57.25	2.16	46.00	2.61	34.75	3.06	23.50	3.51	12.25	3.96	1.00
0.37	90.75	0.82	79.50	1.27	68.25	1.72	57.00	2.17	45.75	2.62	34.50	3.07	23.25	3.52	12.00	3.97	0.75
0.38	90.50	0.83	79.25	1.28	68.00	1.73	56.75	2.18	45.50	2.63	34.25	3.08	23.00	3.53	11.75	3.98	0.50
0.39	90.25	0.84	79.00	1.29	67.75	1.74	56.50	2.19	45.25	2.64	34.00	3.09	22.75	3.54	11.50	3.99	0.25
0.40	90.00	0.85	78.75	1.30	67.50	1.75	56.25	2.20	45.00	2.65	33.75	3.10	22.50	3.55	11.25	4.00	0.00
0.41	89.75	0.86	78.50	1.31	67.25	1.76	56.00	2.21	44.75	2.66	33.50	3.11	22.25	3.56	11.00		
0.42	89.50	0.87	78.25	1.32	67.00	1.77	55.75	2.22	44.50	2.67	33.25	3.12	22.00	3.57	10.75		
0.43	89.25	0.88	78.00	1.33	66.75	1.78	55.50	2.23	44.25	2.68	33.00	3.13	21.75	3.58	10.50		
0.44	89.00	0.89	77.75	1.34	66.50	1.79	55.25	2.24	44.00	2.69	32.75	3.14	21.50	3.59	10.25		

TABLE 2

PAY SCHEDULE FOR RIDE QUALITY USING RIDE QUALITY INDEX (RQI)
(FACTOR TO BE MULTIPLIED BY CONTRACT UNIT PRICE)

Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor	Profile Index	Pay Factor
RQI	%	RQI	%	RQI	%	RQI	%	RQI	%	RQI	%	RQI	%	RQI	%	RQI	%
22.00	100.00	24.60	88.69	27.20	77.39	29.80	66.09	32.40	54.78	35.00	43.48	37.60	32.17	40.20	20.87	42.80	9.57
22.05	99.78	24.65	88.48	27.25	77.17	29.85	65.87	32.45	54.56	35.05	43.26	37.65	31.96	40.25	20.65	42.85	9.35
22.10	99.56	24.70	88.26	27.30	76.96	29.90	65.65	32.50	54.35	35.10	43.04	37.70	31.74	40.30	20.43	42.90	9.13
22.15	99.35	24.75	88.04	27.35	76.74	29.95	65.43	32.55	54.13	35.15	42.83	37.75	31.52	40.35	20.22	42.95	8.91
22.20	99.13	24.80	87.82	27.40	76.52	30.00	65.22	32.60	53.91	35.20	42.61	37.80	31.30	40.40	20.00	43.00	8.70
22.25	98.91	24.85	87.61	27.45	76.30	30.05	65.00	32.65	53.70	35.25	42.39	37.85	31.09	40.45	19.78	43.05	8.48
22.30	98.69	24.90	87.39	27.50	76.09	30.10	64.78	32.70	53.48	35.30	42.17	37.90	30.87	40.50	19.57	43.10	8.26
22.35	98.48	24.95	87.17	27.55	75.87	30.15	64.56	32.75	53.26	35.35	41.96	37.95	30.65	40.55	19.35	43.15	8.04
22.40	98.26	25.00	86.96	27.60	75.65	30.20	64.35	32.80	53.04	35.40	41.74	38.00	30.43	40.60	19.13	43.20	7.83
22.45	98.04	25.05	86.74	27.65	75.43	30.25	64.13	32.85	52.83	35.45	41.52	38.05	30.22	40.65	18.91	43.25	7.61
22.50	97.82	25.10	86.52	27.70	75.22	30.30	63.91	32.90	52.61	35.50	41.30	38.10	30.00	40.70	18.70	43.30	7.39
22.55	97.61	25.15	86.30	27.75	75.00	30.35	63.69	32.95	52.39	35.55	41.09	38.15	29.78	40.75	18.48	43.35	7.17
22.60	97.39	25.20	86.09	27.80	74.78	30.40	63.48	33.00	52.17	35.60	40.87	38.20	29.57	40.80	18.26	43.40	6.96
22.65	97.17	25.25	85.87	27.85	74.56	30.45	63.26	33.05	51.96	35.65	40.65	38.25	29.35	40.85	18.04	43.45	6.74
22.70	96.95	25.30	85.65	27.90	74.35	30.50	63.04	33.10	51.74	35.70	40.43	38.30	29.13	40.90	17.83	43.50	6.52
22.75	96.74	25.35	85.43	27.95	74.13	30.55	62.83	33.15	51.52	35.75	40.22	38.35	28.91	40.95	17.61	43.55	6.30
22.80	96.52	25.40	85.22	28.00	73.91	30.60	62.61	33.20	51.30	35.80	40.00	38.40	28.70	41.00	17.39	43.60	6.09
22.85	96.30	25.45	85.00	28.05	73.69	30.65	62.39	33.25	51.09	35.85	39.78	38.45	28.48	41.05	17.17	43.65	5.87
22.90	96.09	25.50	84.78	28.10	73.48	30.70	62.17	33.30	50.87	35.90	39.56	38.50	28.26	41.10	16.96	43.70	5.65
23.95	95.87	25.55	84.56	28.15	73.26	30.75	61.96	33.35	50.65	35.95	39.35	38.55	28.04	41.15	16.74	43.75	5.44
23.00	95.65	25.60	84.35	28.20	73.04	30.80	61.74	33.40	50.43	36.00	39.13	38.60	27.83	41.20	16.52	43.80	5.22
23.05	95.43	25.65	84.13	28.25	72.83	30.85	61.52	33.45	50.22	36.05	38.91	38.65	27.61	41.25	16.30	43.85	5.00
23.10	95.22	25.70	83.91	28.30	72.61	30.90	61.30	33.50	50.00	36.10	38.70	38.70	27.39	41.30	16.09	43.90	4.78
23.15	95.00	25.75	83.69	28.35	72.39	30.95	61.09	33.55	49.78	36.15	38.48	38.75	27.17	41.35	15.87	43.95	4.57
23.20	94.78	25.80	83.48	28.40	72.17	31.00	60.87	33.60	49.56	36.20	38.26	38.80	26.96	41.40	15.65	44.00	4.35
23.25	94.56	25.85	83.26	28.45	71.96	31.05	60.65	33.65	49.35	36.25	38.04	38.85	26.74	41.45	15.43	44.05	4.13
23.30	94.35	25.90	83.04	28.50	71.74	31.10	60.43	33.70	49.13	36.30	37.83	38.90	26.52	41.50	15.22	44.10	3.91
23.35	94.13	25.95	82.82	28.55	71.52	31.15	60.22	33.75	48.91	36.35	37.61	38.95	26.30	41.55	15.00	44.15	3.70
23.40	93.91	26.00	82.61	28.60	71.30	31.20	60.00	33.80	48.70	36.40	37.39	39.00	26.09	41.60	14.78	44.20	3.48
23.45	93.69	26.05	82.39	28.65	71.09	31.25	59.78	33.85	48.48	36.45	37.17	39.05	25.87	41.65	14.57	44.25	3.26
23.50	93.48	26.10	82.17	28.70	70.87	31.30	59.56	33.90	48.26	36.50	36.96	39.10	25.65	41.70	14.35	44.30	3.04
23.55	93.26	26.15	81.96	28.75	70.65	31.35	59.35	33.95	48.04	36.55	36.74	39.15	25.43	41.75	14.13	44.35	2.83
23.60	93.04	26.20	81.74	28.80	70.43	31.40	59.13	34.00	47.83	36.60	36.52	39.20	25.22	41.80	13.91	44.40	2.61
23.65	92.82	26.25	81.52	28.85	70.22	31.45	58.91	34.05	47.61	36.65	36.30	39.25	25.00	41.85	13.70	44.45	2.39
23.70	92.61	26.30	81.30	28.90	70.00	31.50	58.69	34.10	47.39	36.70	36.09	39.30	24.78	41.90	13.48	44.50	2.17
23.75	92.39	26.35	81.09	28.95	69.78	31.55	58.48	34.15	47.17	36.75	35.87	39.35	24.57	41.95	13.26	44.55	1.96
23.80	92.17	26.40	80.87	29.00	69.56	31.60	58.26	34.20	46.96	36.80	35.65	39.40	24.35	42.00	13.04	44.60	1.74
23.85	91.96	26.45	80.65	29.05	69.35	31.65	58.04	34.25	46.74	36.85	35.43	39.45	24.13	42.05	12.83	44.65	1.52
23.90	91.74	26.50	80.43	29.10	69.13	31.70	57.83	34.30	46.52	36.90	35.22	39.50	23.91	42.10	12.61	44.70	1.30
23.95	91.52	26.55	80.22	29.15	68.91	31.75	57.61	34.35	46.30	36.95	35.00	39.55	23.70	42.15	12.39	44.75	1.09
24.00	91.30	26.60	80.00	29.20	68.69	31.80	57.39	34.40	46.09	37.00	34.78	39.60	23.48	42.20	12.17	44.80	0.87
24.05	91.09	26.65	79.78	29.25	68.48	31.85	57.17	34.45	45.87	37.05	34.57	39.65	23.26	42.25	11.96	44.85	0.65
24.10	90.87	26.70	79.56	29.30	68.26	31.90	56.96	34.50	45.65	37.10	34.35	39.70	23.04	42.30	11.74	44.90	0.44
24.15	90.65	26.75	79.35	29.35	68.04	31.95	56.74	34.55	45.43	37.15	34.13	39.75	22.83	42.35	11.52	44.95	0.22
24.20	90.43	26.80	79.13	29.40	67.83	32.00	56.52	34.60	45.22	37.20	33.91	39.80	22.61	42.40	11.30	45.00	0.00
24.25	90.22	26.85	78.91	29.45	67.61	32.05	56.30	34.65	45.00	37.25	33.70	39.85	22.39	42.45	11.09		
24.30	90.00	26.90	78.69	29.50	67.39	32.10	56.09	34.70	44.78	37.30	33.48	39.90	22.17	42.50	10.87		
24.35	89.78	26.95	78.48	29.55	67.17	32.15	55.87	34.75	44.56	37.35	33.26	39.95	21.96	42.55	10.65		
24.40	89.56	27.00	78.26	29.60	66.96	32.20	55.65	34.80	44.35	37.40	33.04	40.00	21.74	42.60	10.44		
24.45	89.35	27.05	78.04	29.65	66.74	32.25	55.43	34.85	44.13	37.45	32.83	40.05	21.52	42.65	10.22		
24.50	89.13	27.10	77.82	29.70	66.52	32.30	55.22	34.90	43.91	37.50	32.61	40.10	21.30	42.70	10.00		
24.55	88.91	27.15	77.61	29.75	66.30	32.35	55.00	34.95	43.70	37.55	32.39	40.15	21.09	42.75	9.78		

Mississippi Department of Transportation course will be accepted with respect to compaction on a lot to lot basis from density tests performed by the Department. Material produced and placed during the test strip(s) for each course will be designated as separate lots. Otherwise, the size of a lot will be designated as a days production unless terminated by the Engineer. When less than a days production and one or more tests have been made for each of the characteristics of VMA, total voids, asphalt content and stability, the work will be considered as a lot. When less than a days production and no tests have been made for each of the characteristics of VMA, total voids, asphalt content and stability, the work will be included in the previous lot. Each lot will be divided into five approximately equal sublots. One density test will be taken at a random location in each of the sublots in accordance with Department SOP. When a nuclear density test of a sublot does not meet the specified density requirements, two additional tests will be taken within a one-square meter area of the first test. The average of the three tests shall be the density of the sublot, except when removal of the sublot or a portion thereof is required as set-out below. The average of the five sublot density tests will be the test value for the lot. Additional tests may be required by the Engineer to determine acceptance of work appearing deficient.

When determined that the test value for a lot is below 92.0 percent but not lower than 90.0 percent of maximum density, the Contractor will have the right to remove and replace the sublot or sublots not meeting the specified density requirements in lieu of accepting reduced payment for the lot as determined in accordance with the provisions of Subsection 401.05, Basis of Payment.

When determined that the test value for a lot is above 95.0 percent but no higher than 97.0 percent of maximum density, the Contractor shall make the necessary correction(s) to the plant and/or mixture to conform to the specified density requirements. If the next lot, or portion thereof, shows that conformance to the specified density requirements has not been attained, the Contractor's operation will be suspended until such correction(s) is/are made. After a suspension of operations, a new test strip will be required during which the Contractor shall develop a new rolling pattern for compaction to specification requirements. Payment for the mixture placed prior to making correction(s) shall be made in accordance with Subsection 401.05.

When determined that a density is below 90.0 percent or above 97.0 percent of maximum density, the lot, sublot(s) or portions thereof shall be removed and replaced in accordance with the Department's S.O.P. No. TMD-22-06-00-000M at no additional cost to the State. The density will be verified from a pavement sample taken within a one-square meter area of the original nuclear gauge test and tested in accordance with AASHTO Designation: T 166 prior to requiring removal and replacement. The limits of removal will be established from

pavement sample densities. Any required removal shall be full lane width and not less than 15 meters in length. A corrected sublot will be retested for approval and determination of the average test value for the lot in accordance with Department SOP. No resampling will be performed when pavement samples are used for determining density.

401.02.6.5--Acceptance Procedure for Pavement Smoothness. When compaction is completed, the course shall have a uniform surface and be in reasonably close conformity with the line, grade and cross section shown on the plans.

The smoothness of each course will be determined by using a profilograph to produce a profilogram (profile trace) at each designated location. The surface shall be tested and corrected to a smoothness index as described herein with the exception of those locations or specific projects that are excluded from a smoothness test with the profilograph.

The profilograph, furnished and operated by the Contractor under supervision of the Engineer, shall consist of a frame at least 7.5 meters in length supported upon multiple wheels having no common axle. The wheels shall be arranged in a staggered pattern so that no two wheels will simultaneously cross the same bump. A profile is to be recorded from the vertical movement of a sensing mechanism. This profile is in reference to the mean elevation of the contact points established by the support wheels. The sensing mechanism, located at the mid-frame, may consist of a single bicycle-type wheel or a dual-wheel assembly consisting of either a bicycle-type (pneumatic tire) or solid rubber tire vertical sensing wheel and a separate bicycle-type (pneumatic tire) longitudinal sensing wheel. The wheel(s) shall be of such circumference(s) to produce a profilogram recorded on a scale of 1:300 longitudinally and 1:1 (full scale) vertically. Motive power may be provided manually or by the use of a propulsion unit attached to the center assembly. In operation, the profilograph shall be moved longitudinally along the pavement at a speed no greater than five kilometers per hour so as to reduce bounce as much as possible. The testing equipment and procedure shall comply with the requirements of Department SOP.

The smoothness of each course will be determined for traffic lanes, auxiliary lanes, climbing lane and two-way turn lanes. Areas excluded from a smoothness test with the profilograph are acceleration and deceleration lanes, tapered sections, transition sections (for width), shoulders, crossovers, ramps, side street returns, etc. Pavement on horizontal curves having a radius of less than 300 meters at the centerline and pavement within the superelevation transition of such curves are excluded from a test with the profilograph. (A single course overlay is excluded unless the existing surface profile has been corrected by milling or other methods as provided by the contract.) The profilogram shall terminate five meters from each transverse joint that separates the pavement from a bridge deck, bridge approach slab or existing pavement not constructed under the contract.

A profilogram will be made for each course. The measurements will be made in the outside wheel path of exterior lanes and either wheel path of interior lanes. The wheel path is designated as being located 0.9 meter from the edge of pavement or longitudinal joint. The testing will be limited to a single profilogram for each course of a lane except that a second profilogram will be made on these segments that have been surface corrected. Other profilograms may be made only to define the limits that are out of tolerance.

Each course will be accepted on a lot to lot basis for pavement smoothness. Each lot will be sub-divided into sections which terminate at bridges, transverse joints or other interruptions. Each section will be sub-divided into segments of 0.15 kilometer with the remainder of the section also considered a segment. The last five meters of a day's course may not be obtainable until the course is continued and for this reason may be included in the subsequent lot.

A profile index will be determined for each lot as millimeters per kilometer in excess of the blanking band which is simply referred to as the "Profile Index". From the profilogram of each segment, the scallops above and below the blanking band are totaled in millimeters. The totaled count of millimeters for all segments in a lot is converted to millimeters per kilometer to establish a smoothness profile index for that lot.

Individual bumps and/or dips that are identified on the profilogram by locating vertical deviations that exceed 10.0 millimeters when measured from a chord length of 7.5 meters or less shall be corrected regardless of the profile index value of the lot. The Contractor shall also make other necessary surface corrections to ensure that the final profile index of the lot will be equal to or less than the value assigned in 403.03.2, Surface Tolerances.

Lot(s) exceeding the assigned profile index value shall be corrected as specified in 403.03.4. All such correction shall be at the expense of the Contractor.

Scheduling will be the responsibility of the Contractor with approval of the Engineer, and the tests shall be conducted within 72 hours after each day's production unless authorized otherwise by the Engineer. The Contractor will be responsible for traffic control associated with this testing operation.

401.02.7--Nuclear Gauges.

401.02.7.1--Nuclear Moisture-Density Gauge. The nuclear gauge unit shall contain a full data processor which holds all calibration constants necessary to compute and directly display wet density, moisture, and dry density in kilograms

per cubic meter. The data processor shall compute and display the percent moisture and percent density based on dry mass. (Note - State furnished for acceptance testing.)

401.02.7.2--Nuclear Asphalt Content Gauge. The Contractor shall furnish, unless designated otherwise in the contract, a Troxler Nuclear Asphalt Content Gauge (Model 3241 or updated model) or a Campbell Nuclear Asphalt Content Gauge (Model AC-2 or updated model) or an approved equal.

The Engineer will be responsible for calibration and operation of the nuclear gauge.

401.03--Construction Requirements.

401.03.1--Specific Requirements.

401.03.1.1--Weather Limitations. The mixture shall not be placed when weather conditions prevent the proper handling and finishing or the surface on which it is to be placed is wet or frozen. At the time of placement, the air and pavement surface temperature limitations shall be equal to or exceed that specified in the following table:

TEMPERATURE LIMITATIONS

COMPACTED THICKNESS	SURFACE COURSES	BINDER AND LEVELING COURSES	BASE COURSES
Less than 40 mm	13°C	13°C	-
40 mm to 65 mm	10°C	7°C	7°C
More than 65 mm	7°C	5°C	5°C

When paving operations are discontinued because of rain, the mixture in transit shall be protected until the rain ceases. The surface on which the mixture is to be placed shall be swept to remove as much moisture as possible and the mixture may then be placed subject to removal and replacement at the Contractor's expense if contract requirements are not met.

401.03.1.2--Tack Coat. Tack coat shall be applied to previously placed subbase/base course or road surface and between layers, unless otherwise directed by the Engineer. The tack coat shall be applied as a spray coating, fog coating, or "spider webbing". Construction requirements shall be in accordance with 407.03.

401.03.1.3--Rollers. Rollers shall meet the requirements of 401.03.5.

401.03.1.4--Density. The average lot density for all dense graded base and pavement courses, except as provided below for ramp pads, irregular shoulder areas, median crossovers, turnouts, or other areas where the established rolling pattern cannot be performed, and sand asphalt seal courses, shall not

Oklahoma Department of Transportation

RQ SPECIFICATION

Oklahoma Department of Transportation

FOR
PAVEMENT AND BRIDGE FLOORS SMOOTHNESS
PROJECT NO. BRF-030C(122),J/P 06432(04), HARPER COUNTY

These Special Provisions revise, amend and where in conflict, supersede applicable Sections of the Standard Specifications for Highway Construction, Edition of 1988, and the Supplement thereto, Edition of 1991.

Except as noted herein, these Special Provisions apply to all types Portland Cement and asphalt concrete pavements as well as bridge floors constructed as part of this contract or as specified on the Plans.

430.01. DESCRIPTION. This section establishes procedures for determining acceptability and pay adjustments as they relate to smoothness requirements of pavements and bridge floors.

The equipment and testing applicable to this Section shall be provided by the Department and operated by the Department.

430.03. EQUIPMENT. (a) Profilograph. A California Type profilograph will be furnished by the Department for determination of pavement and bridge floor smoothness. This device produces a smoothness profilogram (or profile trace) of the surface tested. The equipment used shall be supported on multiple wheels having no common axle. The wheels shall be arranged in a staggered pattern such that no two wheels cross the same bump at the same time. The profile is recorded from the vertical movement of a sensing wheel attached to the frame at midpoint and is in reference to the mean elevation of the twelve points of contact with the road surface established by the support wheels.

The strip chart recorder shall be mounted on a lightweight frame 25 feet long. The relative smoothness/roughness of the pavement or bridge floor shall be measured by recording the vertical movement of a 6 inch or larger diameter sensing wheel attached to the midpoint of the frame.

The recorded graphical traces of the profile (termed the "profilogram") shall be on a scale of 1 inch equals 1 inch for the vertical motion of the sensing wheel. The profilogram shall be driven by the chart drive on a scale of 1 inch of chart paper equal to 25 feet of longitudinal movement of the profilograph.

(b) Calibration. The profilograph shall be calibrated within the following limits. Horizontal measurements shall be within +/-5 feet per 1,000 feet of distance tested. Vertical measurements shall be the same as those of the calibration blocks measured. A Profilograph Calibration Report shall be submitted to the Engineer each time the calibration is performed. This form will be provided to the contractor by the Engineer. Calibration shall be repeated at the Engineer's direction at any time during the project.

(c) Profilograph Operator. The Department will provide a profilograph operator, qualified to perform all profilograph measurements as well as interpreting and analyzing produced profilograms.

The profilograph will be operated by the Department's profilograph operator.

430.04. CONSTRUCTION. (a) Surface Testing. The Contractor shall provide traffic control as necessary for all profilograph operations. The Department will use an acceptable and approved profilograph for measurement of pavement smoothness. The surface will be tested as soon as possible after completion of the work. For overlay projects when milling is not required, the surface will be tested immediately before construction and as soon as possible after completion of the work in order to determine the percent reduction in the profile index.

Testing shall include all mainline paving and bridge floors. Smoothness deviations occurring at construction and expansion joints will be considered in calculations of profile index and in identification of bumps. Bridge approach slabs will be considered as part of the bridge floor.

All objects and foreign material on the surface shall be removed by the Contractor prior to testing. Protective covers, if used, shall be removed prior to testing and will be properly replaced by the Contractor after testing. Testing for smoothness shall produce a final trace; a second trace shall be made on segments on which surface corrections have been made.

The profilograph shall be propelled at a speed not to exceed 3 miles per hour. Data shall be gathered at lower speeds if the pavement is rough or profilograms are not being produced clearly.

The sequence of positions of the pavement or bridge floor to be tested will be one pass per driving lane in the area most representative of the smoothness in either wheel path.

Additional profiles will be taken only to define the limits of an out-of-tolerance surface variation.

The Department will furnish the profilogram evaluations to the Contractor. The testing and evaluation will be done by a trained and qualified operator and the evaluation will be so certified. The Department reserves the right to verify the testing and/or evaluation. In case of differences the Department's results shall be considered final.

(b) Evaluation.

1. Profile Index. A profile index shall be calculated from the profilogram for pavement or bridge floor 52 feet or more in length, on 528 foot extents. The index will be calculated by the Contractor using a computerized profilogram reduction system. The index is calculated by summing the vertical deviations outside a 0.2 inch blanking band as indicated on the profile trace. The units of this measure (inches) will be converted into inches per 0.1 mile and ultimately into inches per mile. An

extent is defined as the amount of pavement or bridge floorplaced by each 528 foot long pass of a paving machine or finisher. When the quantity represented is 0.05 mile (264 linealfeet) or less in length, it will be combined with an adjacent extent. When it is over 0.05 mile in length, it will be treated as a separate extent.

2. Bumps. Bumps will appear as high or low points on the profile trace and correspond to high or low points on the pavement or bridge floor surfaces. Unacceptable bumps are defined as those with vertical deviations in excess of 0.40 inch (without using a blanking band) in a 25 foot span.

3. Exceptions. Deviations occurring within 25 feet of the beginning and ending stations of the project will be excluded from profile index calculations. Also excluded from these calculations will be deviations occurring on pavements and bridge floors with horizontal centerline curves with a radius of less than 1000 feet and the super elevation transitions of such curves. Any deviations on areas requiring handwork will also be excluded. Shoulders on pavement will be exempt from profilograph testing requirements.

(c) Surface Correction. All new or milled and overlaid pavement and bridge floor surfaces having profile indexes in excess of 12 inches per mile of pavement, 35 inches per mile of Class I bridge floor, or 38 inches per mile of Class II bridge floor and all surfaces having bumps with deviations in excess of 0.40 inch in a 25 foot span shall be corrected by the Contractor at no additional cost to the Department. The Contractor may at his option perform additional corrective action in order to improve the smoothness pay factor. All corrective action shall be in accordance with the requirements of the Standard Specifications and shall be subject to the approval of the Engineer. The surfaces of corrected areas shall be retextured to be similar to that of the adjacent sections of pavement or bridge floor and shall exhibit good workmanship and be neat in appearance. After all required corrective work is completed, the profile index will be redetermined and recorded as the final profile index for that segment. Cores for thickness determinations will be taken subsequent to all correction work.

430.06 BASIS OF PAYMENT. Pay factors for smoothness of pavement and bridge floor will be determined based on final average profile indexes or calculated percent reduction in average profile index, after all corrective actions have been completed for each extent. The pay factor for extents that are corrected on the surface course will be limited to a maximum of 1.00.

The smoothness pay adjustment will be determined for each extent in accordance with the following formula:

$$PA = (Sm-1)\ (CUP)\ (Qe)$$

Definitions of Abbreviations

PA = Smoothness Pay Adjustment ($)
CUP = Contract Unit Price ($/TON, $/S.Y., or $/C.Y.) for each pay item
SM = Pay Factor for Smoothness
Qe = Quantity of Contract Pay Item in an Extent (TON, S.Y., or C.Y.)

The quantity of P.C. concrete pavement in the extent will be the square yards of concrete in the driving lanes.

The quantity of asphalt pavement in the extent will be the full depth including newly placed base layers, or overlay tonnage of asphalt concrete in the driving lanes. Driving lane is defined as a thoroughfare with a lane width of 12 feet. Tonnage will be determined from unit weights from the project job mix formula and typical sections as shown on the Plans.

The quantity of bridge floor in the extent will be the theoretical volume in cubic yards of concrete which is in the driving lanes.

Determination of the resulting smoothness pay factors will be in accordance with the tables shown below:

TABLE I
ROADWAY (TONS OR S.Y. OF PAVEMENT)
For Newly Constructed or Milled and Overlaid Surfaces

Pay Factor, Sm	Profile Index (in./mi.) Class I*	Class II*	Class III*
1.03	Less than 3.0	Less than 5.0	Less than 7.0
1.02	3.0 thru 3.9	5.0 thru 5.9	7.0 thru 7.9
1.01	4.0 thru 4.9	6.0 thru 6.9	8.0 thru 8.9
1.00	5.0 thru 7.0	7.0 thru 9.0	9.0 thru 11.0
.99	7.0 thru 8.0	9.0 thru 10.0	11.1 thru 12.0
.97	8.1 thru 9.0	10.1 thru 11.0	12.1 thru 13.0
.95	9.1 thru 10.0	11.1 thru 12.0	13.1 thru 14.0
.90	10.1 thru 11.0	12.1 thru 13.0	14.1 thru 15.0
.80	11.1 thru 12.0	13.1 thru 14.0	15.1 thru 16.0
Unacceptable	More than 12.0	More than 14.0	More than 16.0

*Class I roads are rural in nature and/or have few, if any, intersecting roads, drainage inlets, or other features which significantly increase the difficulty in obtaining a smooth roadway surface. Class II and Class III roads are urban in nature and/or do have these features which significantly increase the difficulty. When applicable, the road classification is shown in the Plan Notes, or in Special Provision 643-5QA a part of this contract. The classification shown is final and will be used as a basis for payment.

TABLE II
ROADWAY (TONS OR S.Y. OF PAVEMENT)
For Overlays When Milling is Not Required

Pay Factor, Sm	Reduction in Profile Index (percent)
1.00	75 or more
.99	70 to 74
.97	65 to 69
.95	60 to 64
.90	55 to 59
.80	50 to 54
Unacceptable	Less than 50

NOTE: In the event that the pay factor from Table II is less than the pay factor that would be established by using Table I, the pay factor will be derived from Table I.

TABLE III
BRIDGE FLOOR (CU.YD. OF CONCRETE)

Pay Factor, Sm	Profile Index (in./mi.) Class I*	Class II*
1.05	Less than 15.0	Less than 18.0
1.04	15.1 thru 16.3	18.1 thru 19.3
1.03	16.4 thru 17.5	19.4 thru 20.5
1.02	17.6 thru 18.8	20.6 thru 21.8
1.01	18.9 thru 20.0	21.9 thru 23.0
1.00	20.1 thru 25.0	23.1 thru 28.0
.99	25.1 thru 28.0	28.1 thru 31.0
.98	28.1 thru 29.0	31.1 thru 32.0
.97	29.1 thru 30.0	32.1 thru 33.0
.96	30.1 thru 31.0	33.1 thru 34.0
.95	31.1 thru 32.0	34.1 thru 35.0
.94	32.1 thru 33.0	35.1 thru 36.0
.92	33.1 thru 34.0	36.1 thru 37.0
.90	34.1 thru 35.0	37.1 thru 38.0
Unacceptable	More than 35.0	More than 38.0

*Class I bridge floors are those that do not present significant special problems in obtaining desired smoothness due to geometry of the bridges. Class II bridge floors are those that do present significant special problems due to geometry. Geometric features considered in classifying bridge floors include but are not limited to skews, changes in widths, changes in super elevations and very sharp vertical or horizontal curves. When applicable, the bridge floor classification(s) is shown in the Plan Notes, or in Special Provision 643-5QA a part of this contract. The classification shown is final and will be uses as a basis for payment.

Incentive for Consistently Smooth Pavement and Bridge Floors

In addition to the pay adjustments on pavement and bridge floor extents, a 2.0% bonus will be paid for mainline pavements and bridge floors that are consistently smooth throughout the entire project length. To be eligible for the bonus a pavement project must have no extents with roughness factors in excess of 6.0 inches per mile and a bridge project no roughness factors, in excess of 23.0 inches per mile (Class I) or 26.0 inches per mile (Class II) before any grinding or other corrective measures, except for total slab replacement. The quantity to which the 2.0% bonus will apply will be total of those quantities computed for the individual extents. This incentive provision applies to all newly constructed roadways, overlays of milled surfaces, and overlays when milling is not required (everything in Tables I, II, and II above.)

Texas Department of Transportation

RQ SPECIFICATION
<u>Texas Department of Transportation</u>

SPECIAL SPECIFICATION

ITEM 5237

RIDE QUALITY FOR PAVEMENT SURFACES

1. Description. This Item shall govern the evaluation of ride quality for pavement surfaces.

2. General. The finished surface of the pavement shall be smooth and true to the established line, grade and cross section shown on the plans. Surface Test Type A shall be used on all pavement surfaces including intermediate layers. When shown on the plans, Surface Test Type B shall apply longitudinally along the finished riding surface of all travel lanes, including service roads, unless specific areas are excluded or other areas are designated for Surface Test Type B. The transverse slope of the finished riding surface will be tested in accordance with Surface Test Type A.

3. Testing Procedures. The surface finish shall be tested by the Contractor in accordance with the requirements below.

   (1) Surface Test Type A. The surface or layer shall be tested with a 10 foot straightedge at locations selected by the Engineer.

   (2) Surface Test Type B. The surface or layer shall be tested using a profilograph in accordance with the requirements of Test Method Tex-1000-S.

   A profilograph meeting the requirements of Test Method Tex-1000-S shall be furnished and maintained by the Contractor. The equipment shall be calibrated by the Contractor and calibration verified by the Engineer in accordance with Test Method Tex-1000-S prior to its use on the project. Unless otherwise shown on the plans, the Contractor shall propel the profilograph under the direction of the Engineer. The results of the profilograph test will be evaluated by the Contractor's Level IB Certified Specialist and verified by the Engineer's Level IB Certified Specialist in accordance with Test Method Tex-1000-S. A properly calibrated automated profilograph will be allowed for all pavement surfaces.

   a. Scope. Testing will be limited to those pavement surfaces having a construction length of 0.1 mile or more. Pavement with horizontal curves having a centerline radius of curvature less than 1000 feet and the superelevation transition to such curves will not be profiled. Pavement within 15 feet of a transverse joint which separates the pavement from an existing pavement not placed by this project, a bridge structure or an approach slab will not be subjected to this test. These areas shall be evaluated using the 10 foot straightedge as outlined in Subarticle 3.(1). and 4.(1).

b. Pavement Profiles. Pavement profiles will commence 15 feet into the previous placement and will be taken along both of the approximate wheel paths of each travel lane. The profile location will normally lie three (3) feet from and parallel to the approximate location of the pavement lane lines. The profile index used for evaluating each 0.1 mile section of each travel lane to determine its payment bonus or deduction shall be the average of these two (2) profiles. The profilograph will be used to identify the limits of an out-of-tolerance surface variation.

c. Initial Paving Operation. During the initial day of paving operations, the pavement surface shall be tested with the profilograph as soon as possible without damaging the pavement surface. The purpose of this initial testing is to aid the Contractor and the Engineer in evaluating the paving methods and equipment. When the paving methods and paving equipment do not result in a negative pay adjustment calculation, the Contractor may proceed with the paving operation.

When this initial paving operation results in a negative pay adjustment calculation, the Contractor shall make correction in the paving operations before proceeding. There will be no pay adjustment for the initial day of paving unless the Contractor elects to waive the requirements and begin acceptance testing in accordance with Article 4 and pay adjustments in accordance with Article 5. This notification must be made in writing to the Engineer prior to the first day of paving.

d. Daily Average Pay Adjustment. The daily average pay adjustment is obtained by averaging the pay adjustments of all 0.1 mile sections of pavement placed during each day's paving.

When the daily average pay adjustment for any day results in a pay deduction, the Contractor shall evaluate the paving operation.

When two consecutive daily average pay adjustments result in a pay deduction, the Contractor shall take corrective action in the paving operation.

When three consecutive daily average pay adjustments result in a pay deduction, operation shall cease until test results, or other information indicate to the satisfaction of the Engineer that the next material to be placed will not result in a daily average pay deduction.

4. Pavement Evaluation and Corrections.

(1) Surface Test Type A. The variation of the surface from the testing edge of the straightedge shall not exceed 1/8 inch between any two (2) contacts, when measured longitudinally or transversely. All irregularities exceeding the specified tolerance shall be corrected as approved by the Engineer at the Contractor's expense. Following correction, the area shall be retested to verify compliance with this Item.

(2) Surface Test Type B. After the pavement surface has been tested, all areas having deviations in excess of 0.3 inch in 25 feet or less shall be corrected unless otherwise directed by the Engineer. Following correction, the area shall be retested to verify compliance with this Item.

After acceptance of all individudal deviations noted above, any 0.1 mile section having an adjusted profile index of over 12.0 shall be corrected to produce a profile index of 6.0 or less. On those 0.1 mile sections where corrections are required, the corrected pavement section shall be reprofiled to verify that corrections have produced the required improvements.

When the pay adjustment results in any pay deduction on any 0.1 mile section, the Contractor may elect to accept the pay deduction on that 0.1 mile section in lieu of taking corrective actions to reduce the profile index. The Contractor will not be allowed to improve the ride quality on sections with an adjusted profile of 6.0 or less if the modifications are made for the sole purpose of increasing the bonus payment for that section.

All corrective work shall be at the Contractor's expense.

The Contractor shall demonstrate that any proposed corrective work will produce results satisfactory to the Engineer.

5. Pay Adjustment. The pay adjustment for ride quality will be determined as follows:

(1) Surface Test Type A. No pay adjustment will be made when Surface Test Type A is used.

(2) Surface Test Type B. Pay adjustment will be made in accordance with the following appropriate schedule. No bonus will be paid for pavement sections which were originally constructed under this Item with a pay deduction. There will be no pay adjustments for the sections where the Contractor took corrective action.

(a) Hot Mixed Asphalt Pavements where:
- o Total construction thickness is composed of at least 1.5 inch surfacing and 1.0 inch of level-up for a minimum total thickness of 2.5 inches, or
- o Construction is preceded by milling to grade, or
- o Construction is preceded by reestablishment of grade by in-place recycling techniques.

(b) Concrete Pavements *
- o Newly constructed concrete pavements, or
- o Concrete overlays of at least 4.0 inches.

* For concrete pavements, compliance with the Profile Index listed herein shall be determined by subtracing 4.0 from the actual field measured profilograph reading. This 4.0 deduction is intended to compensate for any roughness induced to the freshly placed concrete such as those due to required "tining" of the surfacing.

<u>Pay Adjustment Schedule For Ride Quality</u>

*Profile Index per each 0.1 Mile Section	Posted Speed > 45 MPH Pay Adjustment	Posted Speed < 45 MPH Pay Adjustment
1.5 or less	+$90	+$90
1.6 thru 2.0	+$70	+$70
2.1 thru 3.0	+$50	+$50
3.1 thru 4.0	+$35	+$35
4.1 thru 6.0	$0	+$20
6.1 thru 8.0	-$35	$0
8.1 thru 9.0	-$50	-$20
9.1 thru 10.0	-$70	-$50
10.1 thru 11.0	-$105	-$105
11.1 thru 12.0	-$140	-$140
Over 12.0	Corrective work required	

6. <u>Measurement and Payment</u>. The work performed, materials furnished and all labor, tools, equipment and incidentals necessary to complete the work under this Item will not be measured or paid for directly, but will be considered subsidiary to the various bid items of the contract.

The pay adjustment as shown in the appropriate schedule above will be paid or deducted separately.

APPENDIX 4

Photographs of Ride Quality Devices

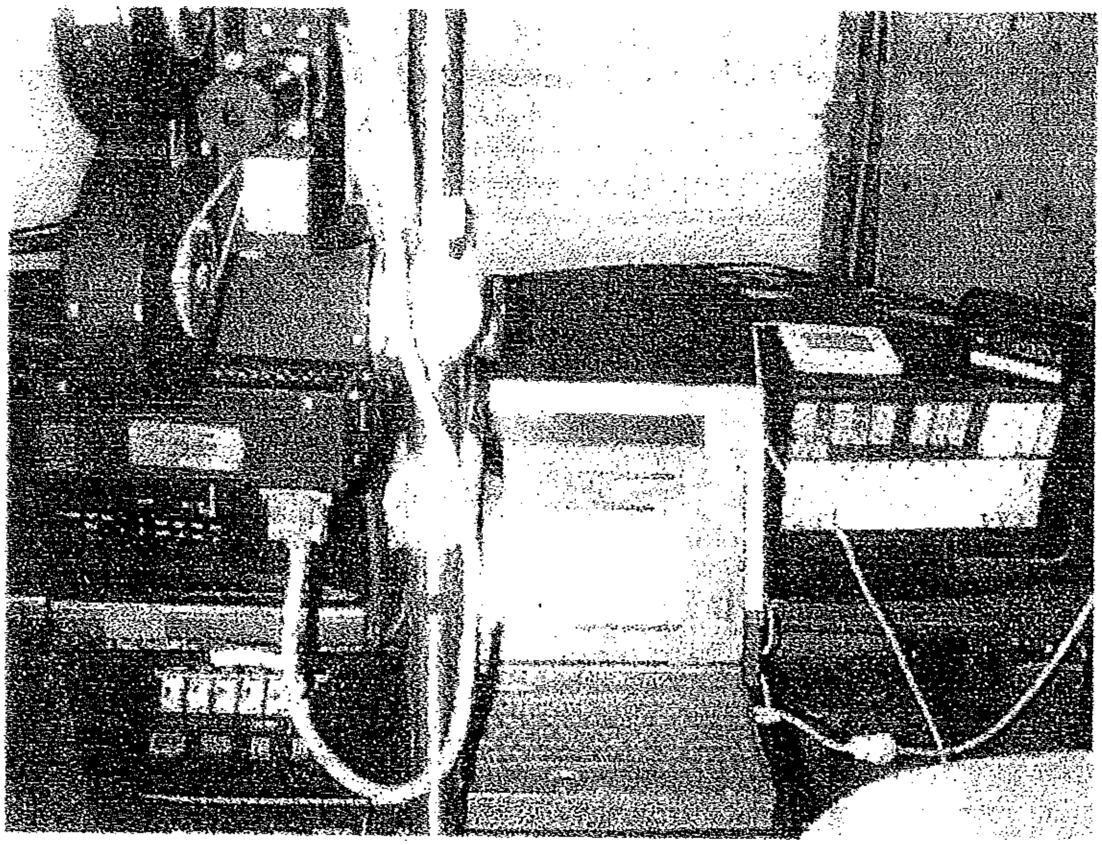


Figure A_4.1 Connecticut DOT's ARAN Video and Data Processing Center

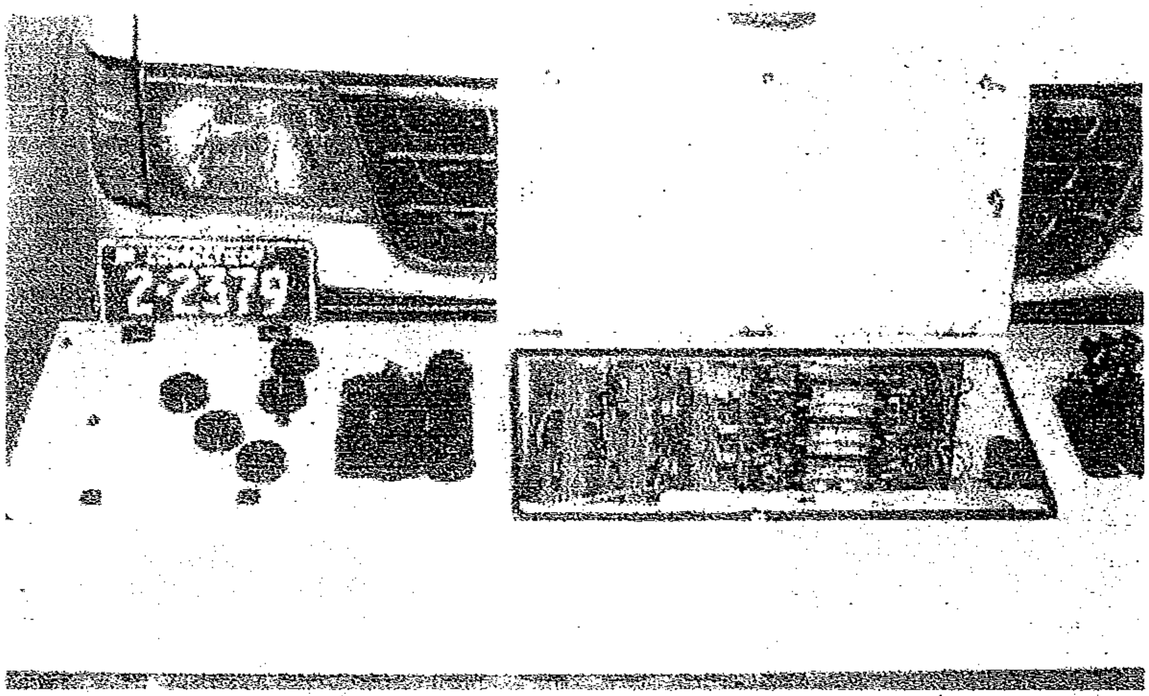


Figure A_4.2 Connecticut DOT's ARAN Laser System

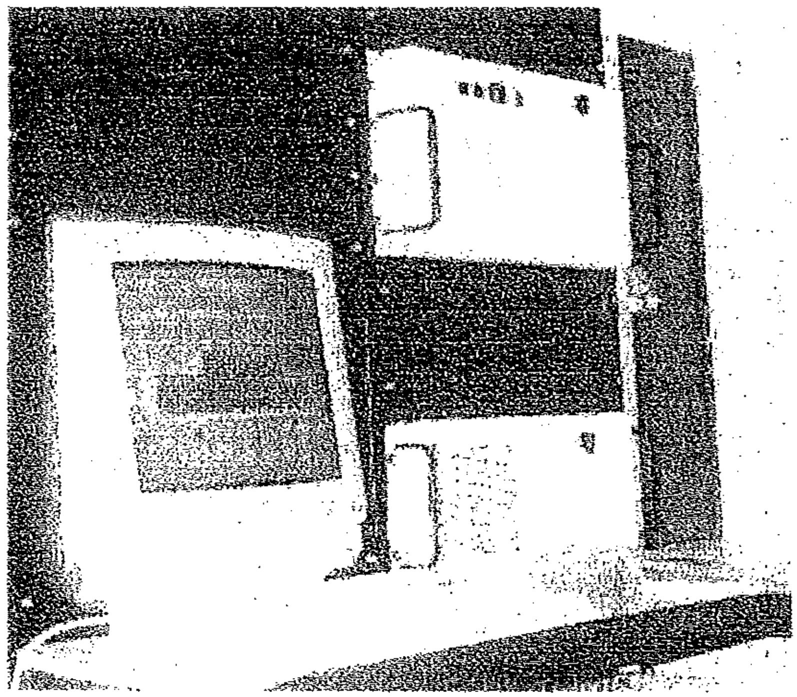


Figure A_4.3 Connecticut DOT's ARAN Data Recording Center

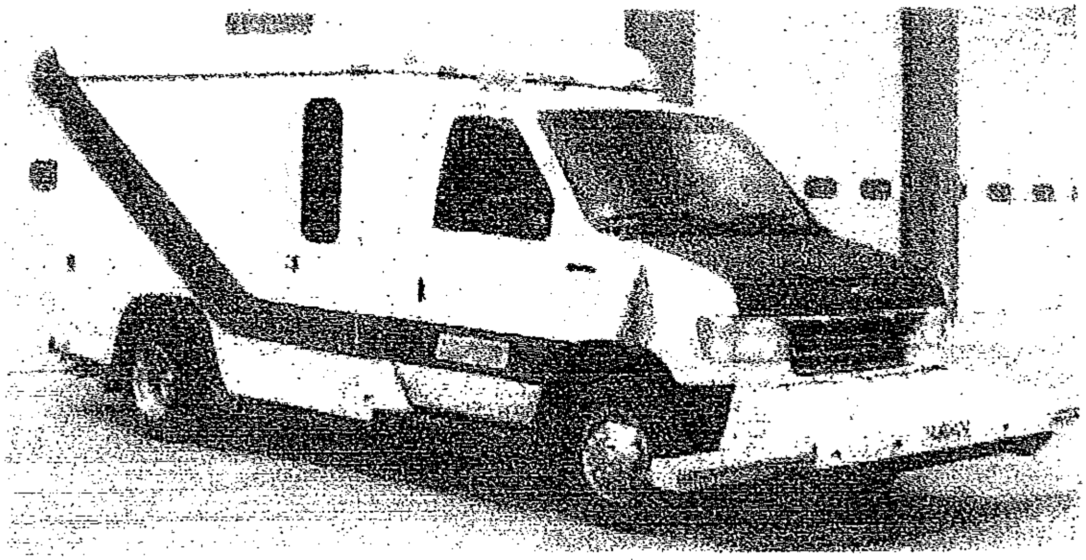


Figure A_4.4 Massachusetts Highway Department ARAN

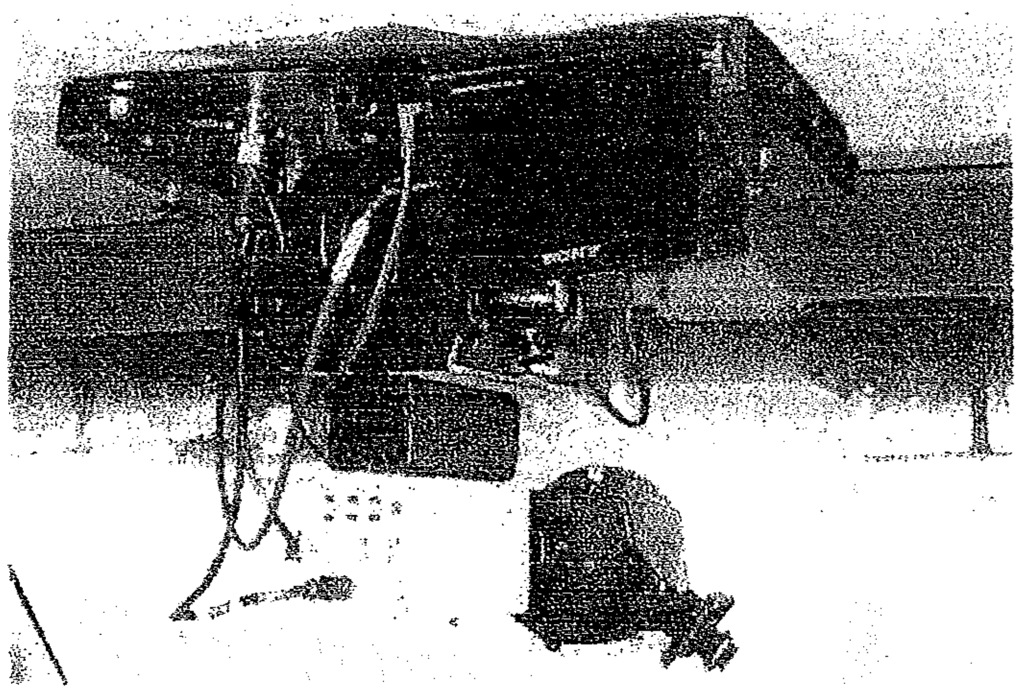


Figure A_4.5 Massachusetts Highway Department's ARAN Video Image Recorder

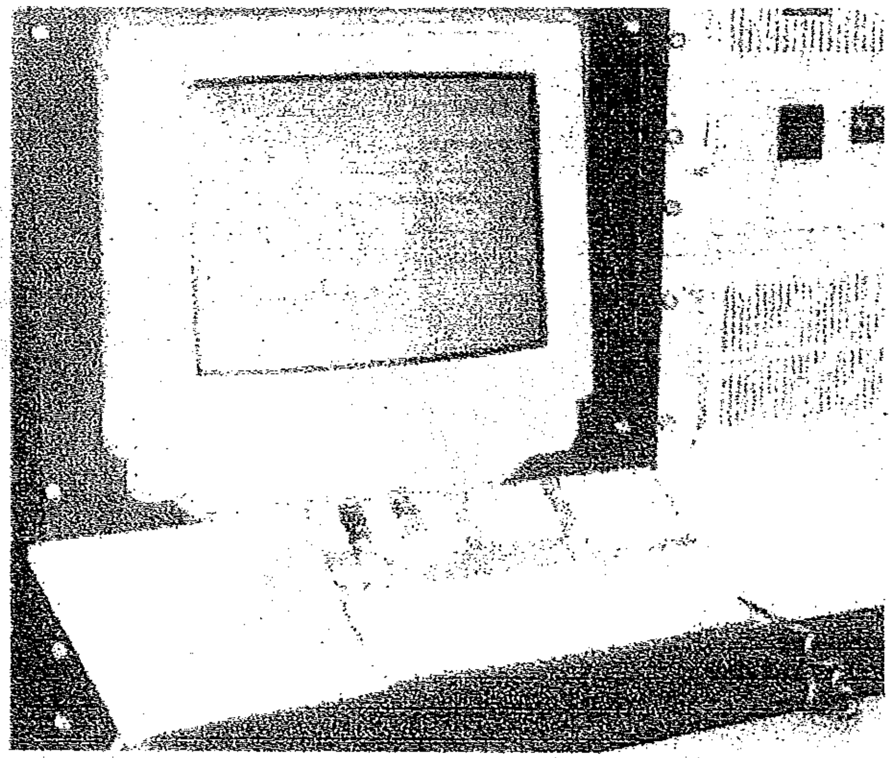


Figure A_4.6 Massachusetts Highway Department's ARAN Data Recording Center

Figure A_4.7 New Hampshire's K.J. Law Profilometer

Figure A_4.8 New Hampshire's K.J. Law Profilometer Data Processing Unit

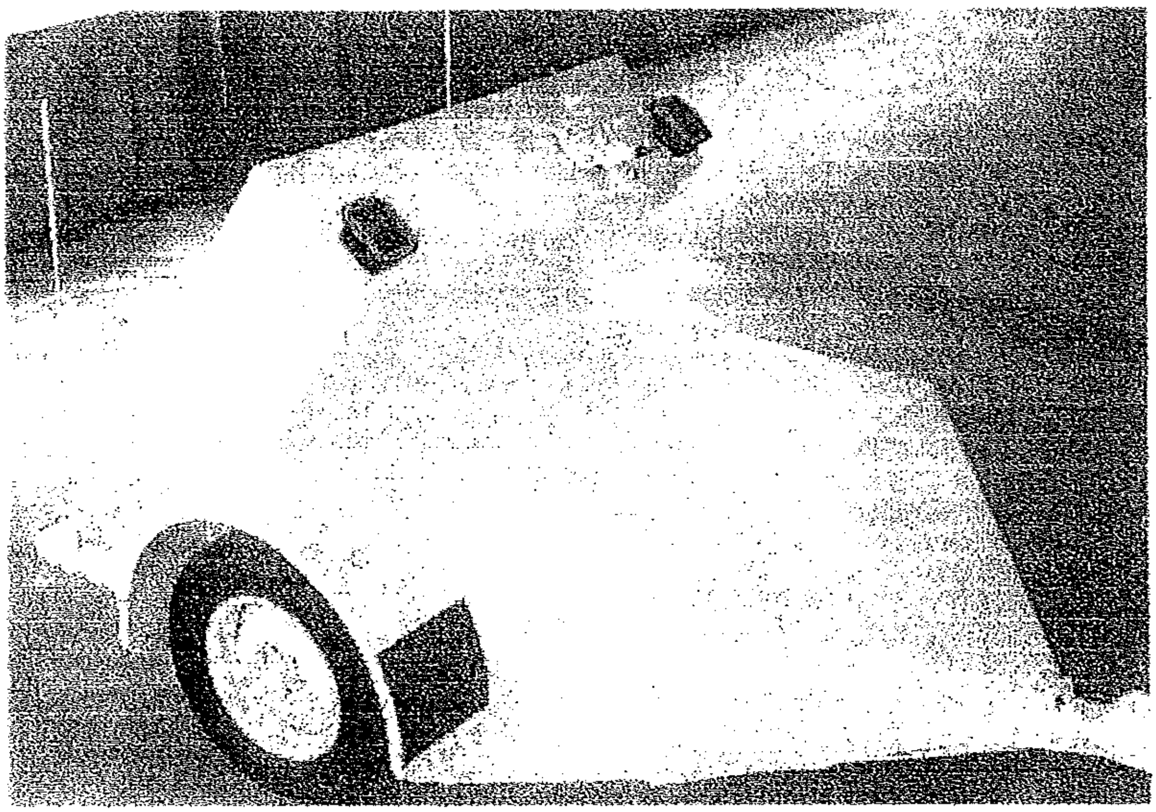


Figure A_4.9 Vermont's Mays Meter Trailer

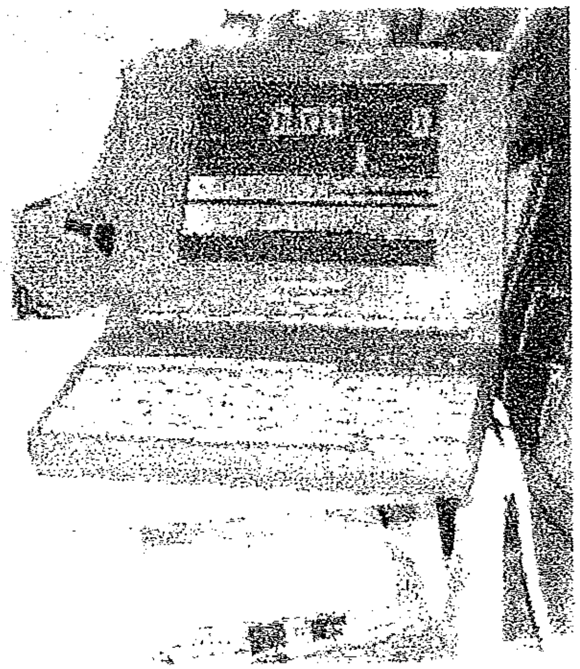


Figure A_10 Vermont's Data Processing Center

APPENDIX 5

Proposed RQ Specification

A Proposed RQ Specification[1]

(1) General

(1.1) The contractor in cooperation with the state highway agency (SHA) shall determine the smoothness of a Hot Mix Asphalt (HMA) surface with the use of a smoothness measuring device. Smoothness data should be collected within 24 hours of completion of the paving portion of the project and the results should be presented to the SHA as soon as possible (according to the requirement of individual state).[2]

(1.2) All paving projects requiring a minimum of two courses in which the compacted depth of each course is 1.5 inches (38.1 mm) or greater are subject to this specification[3]

(1.3) While the smoothness of all HMA pavement projects must be measured and corrected as necessary to meet minimum standards contained in this specification, the following projects are <u>not</u> subject to the pay adjustments discussed in section (4.1.2) of this specification[4]

(1.3.1) Existing pavement that are milled, then resurfaced with less than 2 inches (50.8 mm) of HMA.
(1.3.2) Existing pavement that are cold recycled, then resurfaced with less than 2 inches (50.8 mm) of HMA.

(1.4) The following project sections[5] are specifically excluded from all terms of this specification unless otherwise stated:

(1.4.1) Bridge decks and joints;
(1.4.2) Acceleration and deceleration lanes;
(1.4.3) Shoulders and ramps;
(1.4.4) Pavement on horizontal curves which have a 900 feet (274.32 m) or less centerline radius of curvature and pavement within the superelevation transition of curves;
(1.4.5) Existing roadways that are resurfaced and are less than 1000 feet (304.8 m) in length.

The above project sections will be tested for smoothness with a straightedge or stringline.

(2) Equipment.

(2.1) The data necessary to calculate the IRI will be collected with a smoothness measuring device of the contractor's choice, subject to the approval of the SHA. This device should be a Class I or Class II device as defined by the American Society for Testing Materials (ASTM-E950). Where necessary and appropriate, as deemed by the SHA, a straightedge may be employed to supplement the use of the Class I or Class II device.

(3) **International Roughness Index.**

(3.1) The final pavement surface shall be evaluated for smoothness using a device capable of calibrating the International Roughness Index (IRI) as defined by the World Bank[6]. The IRI is a mathematical summary of the longitudinal surface profile of a roadway in a wheel path. The IRI represents the response of a typical passenger vehicle as a result of a road's roughness. A value of zero is perfectly smooth pavement surface and values greater indicate rougher surfaces. The IRI is independent of distance traveled; thus, it can be calculated for any length of section. The IRI value is computed from the surface elevation data collected by a smoothness measuring device in one wheel path.

(3.2) Payment is based on the smoothness of the road measured in IRI units. The following steps will be carried out to obtain IRI measurements:

(3.2.1) All data will be referenced by mile from the nearest mile post prior to the newly constructed section. If the section beginning coincides with a mile post, then all data will be referenced from the mile post one mile prior to the section.

(3.2.2) Only mainline travel lanes will be included. Profile testing will be suspended two hundredths of a mile prior to the first and two hundredths of a mile after the last expansion joint on bridge decks. The exact location for the suspension and resumption will be determined and recorded in the field by the device operator. These locations will be used for all test runs in all mainline travel lanes.

(3.2.3) Data collection will cease at the nearest mile post after the end of the newly constructed section.

(3.2.4) All data will be collected at sampling intervals of a maximum of 2.0 feet (0.710 m) along the length of the road in both the left and right wheel paths and will be reported in 0.1 mile intervals.

(3.2.5) The IRI value for each lane will be measured in each wheel path at least twice and less than fifth (The exact number of runs should follow the requirement of the individual state).

(3.2.6) The IRI data for the acceptable passes will be averaged for each lane and an overall average IRI will be determined for each lanes for each 0.1 mile (0.161 km) interval.[7] All IRI values measured should be involved in the calculation.

(4) **Payment Adjustment Criteria.**

(4.1) Payment on smoothness will be made for each 0.1 mile (0.161 km) interval or group of intervals based on the average IRI. Pavement will be as follow:

(4.1.1) Any interval (or group of intervals) resulting in zero payment shall be removed, disposed of and replaced at the cost of the Contractor.

(4.1.2) Payment factors are as follows:[8]

Percent Payment (PF_1)	Average IRI
110	< 50.0
105	50.1 - 60.0
100	60.1 - 80.0
90	80.1- 90.0
80	90.1 - 100.0
50	100.1 - 110.0
0	> 110.1

(4.1.3) If the IRI at 0 percent payment is exceeded, construction must be suspended and will not be allowed to resume until corrective action is taken by the contractor.

(5) **Corrective Actions.**

(5.1) After paving has ceased all areas shall be inspected by the engineer and any area within a 25' foot (4.572 m) straightedge having high points (bumps) or low points with deviations in excess of 3/10 inch shall be corrected regardless of the IRI value.

(5.2) The corrective method(s) chosen by the Contractor shall be subject to the approval of the Engineer and shall be performed at the Contractor's expense. The Contractor shall retest any section where corrections were made to verify that the corrections have been made to the approval of the engineer.[9]

Note:

1. This ride quality (RQ) specification is proposed as a guide to assist those state highway agencies (SHAs) in New England who are in the process of formulating and implementing such specification. While it is recognized that some SHAs are further along in the process than others, this proposed specification may be more useful and instructive to those SHAs which are in the early stages of the process. It should also be noted that this RQ specification is proposed for use on highway projects with flexible pavements including a hot mix asphalt (HMA) wearing surface.
2. It is proposed that the costs incurred by the contractor to collect and analyze smoothness data be included in the total project bid price.
3. It is recognized that paving practices and procedures including number of courses and the thickness of each course may vary from project to project within each state and from state to state. Consequently, some SHAs may desire to modify this provision in concert with their current paving procedures.
4. An underlying aim of this provision is to encourage to the extent possible the highest level of ride quality on all paving projects regardless of surface thickness. However, it is recognized that overlays of less than 2 (50.8 mm) inches even when applied over a prepared surface may not be able to achieve the smoothness levels of a thicker overlay with multiple lifts.

5. Measuring smoothness on (or near) bridge decks, speed change lanes, and ramps may require special treatment due to the presence of joints and certain geometric characteristics; hence, for simplicity and ease of implementation, these roadway sections have been excluded from this proposed specification.
6. Other measures, such as the Ride Number (RN) and Ride Quality Index (RQI) may also be considered for use.
7. It should be noted that some SHAs may prefer for ease and simplification purposes to estimate an overall average IRI for the entire roadway project, rather than to estimate IRI in 0.1 mile intervals.

8. Because an average IRI value may not sufficiently capture the variation in IRI over the entire length of the group of intervals, it may be decided by some SHAs that a measure of variation (e.g. standard deviation) should be used together with the average IRI. The illustrative examples below demonstrate the use of the standard deviation:

Example #1:

A group of 0.1 mile (0.161 km) intervals consisting of 500 tons of HMA has an IRI value of 70 (1.105 m/km) with a standard deviation 22.0. Assume that HMA is $30 / ton.

From 4.1.2 and Table 1 below:

PF_f = Final Payment Factor = ($PF_1 + PF_2$)
= (100 + 0) = 100

Total Payment = (PF_f / 100)($ / ton)(Quantity in tons)
= (1.00)($30.00)(500) = $15,000.00

Example #2:

A group of 0.1 mile intervals consisting of 500 tons of HMA has an IRI value of 70 (1.105 m/km) with a standard deviation 9.0. Assume that HMA is $30 / ton.

From 4.1.2 and Table 1 below:

PF_f = Final Payment Factor = ($PF_1 + PF_2$)
= (100 + 6) = 106

Total Payment = (PF_f / 100)($ / ton)(Quantity in tons)
= (1.06)($30.00)(500) = $15,900.00

TABLE 1

Percent Payment (PF_2)	Standard Deviation
+ 6 %	0 - 10
+ 4 %	10.1 - 15.0
+ 2 %	15.1 - 20.0
0 %	20.1 - 25.0
- 2 %	25.1 - 30.0
- 4 %	30.1 - 35.1
- 6%	> 35.1

9. Corrective actions might include:
a) Demand grinding or use of other profiling devices;
b) Removing and replacing the entire pavement thickness;
c) Removing the surface by milling and applying a lift(s) of the specified

surface course;

d) Overlaying (not patching) with the specified surface course;

e) Use the other methods that will provide the desired results;

APPENDIX 6

International Roughness Index (IRI) Computation

IRI computation

The International Roughness Index (IRI) is a standard measure for determining road roughness. It is a product of The International Road Roughness Experiment (IRRE) conducted in Brazil in 1982. [9] The IRI is a complex mathematical simulation of the response of a car traveling over a road surface to roughness. It is the summation of accumulated vehicle suspension displacement divided by distance traveled. Its technical name is the Reference Average Rectified Slope. The most common units are either meters per kilometer (m/km) or inches per mile (in/mi). Low values of the IRI indicate a smooth riding quality and high values indicate a rough ride quality. [10]

The IRI acts as a filter considering only profile information that lies within a 4 foot to 100' waveband. Research has shown that these roughness wave lengths are most objectionable to rider comfort. As a result, the effects of long wave length hills and valleys, and very short wave length surface texture are minimized.

The IRI is a charecteristic of a wheelpaths longitudinal profile. To determine the IRI, profile measurements must be made and recorded. This can be done either manually with a class I survey, or collected by a class II profiler. Alternately a device can be used that has been calibrated to a test profile that was measured with precise means.

The following development is taken from reference 10

From profile measurements, the IRI is calculated by solving the following set equations, for each data point.

$$Z_1 = s_{11} * Z_1' + s_{12} * Z_2' + s_{13} * Z_3' + s_{14} * Z_4' + p_1 * Y'$$

$$Z_2 = s_{21} * Z_1' + s_{22} * Z_2' + s_{23} * Z_3' + s_{24} * Z_4' + p_2 * Y'$$

$$Z_3 = s_{31} * Z_1' + s_{32} * Z_2' + s_{33} * Z_3' + s_{34} * Z_4' + p_3 * Y'$$

$$Z_4 = s_{41} * Z_1' + s_{42} * Z_2' + s_{43} * Z_3' + s_{44} * Z_4' + p_4 * Y'$$

The system must be initialized for tha first data point as described on the following page.

The coefecients s_{ij} and p_j are functions of both vehicle response and the sampling interval. They are tabulated for various sampling intervals, and presented in Ref. 10. one set of coefecients for a sampling interval d_x of 152.4mm (0.50 ft.) the values are as follows.

ST				PR
.9986576	6.727609E-03	3.30789E-05	1.281116E-04	1.309621E-03
-.3717946	.9634164	-.1859178	3.527427E-02	.5577123
8.791381E-03	8.540773E-04	.8992078	5.787373E-03	9.200091E-02
2.388208	.2351618	-27.58257	.6728373	25.19436

The values Y' are the slope at each profile point, given by;

$$Y' = (Y_i - Y_{i-1})/d_x$$

The values Zj' are the Zj values from the previous profile point, j-1,4.

To initialize the system of equations, the following values are set for the first point

$$Z_1' = Z_3' = (Y_a - Y_1) / 11$$

Y_a is the profile elevation @ the "a[th]" point
Y_1 is the profile elevation @ the first point
Z_1 and Z_3 are average slopes over 11 meter interval

$$Z_2' = Z_4' = 0$$

- Z_2 and Z_4 are set to 0

$$a = 11 / dx + 1$$

dx is the measurement interval

$$Y' = (Y_i - Y_{i-1}) / dx$$

approximate instantaneous slope at point i

$$Z_j' = Z_j$$

reset from previous sample point, j=1,4

$$RS_i - | Z_3 - Z_1 |$$

the rectified slope of the filtered profile for a given point

$$IRI = \frac{1}{(n-1)} \sum_{i=2}^{n} RS_i$$

The IRI is the average of the rectified slope taken over all the profile points, (n)

Appendix 7

Comparative Summary of State of the Art Equipment

Comparative Summary of State of the Art Equipment

Equipment (Manufacturer)	**ROLLING DIPSTICK** (FACE CONSTRUCTION TECHNOLOGIES, INC)	**LWP (T6400)** (K.J.LAW)	**RSP (T6500)** (K.J.LAW)	**LASERLUX** (ROADWARE, INC)
Est.Price	$25,000(1995 Price)	$60,000	$165,000	$200,000
Speed	4mph	5-15mph	20-70mph	0-60mph
Lane Closure Requirement	Yes	Yes	No	No
Weather Condition Requirement	Yes	Yes	No	No
Contact Person	Darrell L, Darrow	Wade M, Jenson	Wade M, Jenson	Ivan V, Deen
Address	427w, 35th Street Norfolk, VA 23508 Tel: 804-624-2121 Fax: 804-624-2128	42300W.Nine Mile Road Novi, Michigan 48375-4103 Tel: 800-521-5245 Fax:,810-374-3345	42300W.Nine Mile Road Novi, Michigan 48375-4103 Tel: 800-521-5245 Fax:,810-374-3345	147 East River Road P.O.Box 520 Paris, Ontario N3L 3T6 Tel: 519-442-2264 Fax: 519-442-3680

* As of May 1997

Appendix 8

Annotated Bibliography

Ride Quality Acceptance of Pavements

Annotated Bibliography

1.

Moulthrop, James S.; Day, Larry; Ballou W.R.; **Initial Improvement in Ride Quality of a Jointed, Plain Concrete Pavement (JPCP) with Microsurfacing: A Case Study.** Moulthrop technologies Inc., Ballou Construction Co., and Koch Materials Co., A Draft Submitted to the Transportation Research Board, 1996.

Abstract:

This paper describes a case study in Cowley, Kansas where the ride quality of an existing jointed, plain concrete pavement (JPCP) was significantly improved by the placement of a thin, polymer modified asphalt emulsion microsurfacing system. The existing pavement conditions, the construction techniques used by the contractor, and the smoothness measurements before and after construction are noted and discussed.

The conclusions note that a marked reduction in roughness can be accomplished with unique construction techniques and microsurfacing.

Report related to SHA Survey Questions: 1, 2, and 3.

2.

Zhu, J. Jim; Zhu, Wenli; Smailus, Thomas; Martinez, Mark; **Evaluation and Implementation of an Automated Profilogram Reduction System: APPARE.** Remote Sensing and Image Processing Laboratory and the Louisiana Transportation research Center, A draft submitted to the Transportation Research Board, 1996.

Abstract:

APPARE is PC based scanner/software system for Automated Pavement Profile Analysis and Roughness Evaluation, developed for the Louisiana Department of Transportation and Development (LDOTD) / Louisiana Transportation Research Center (LTRC). In this paper, field evaluation results conducted by the LTRC and districts 03, 04 and 62 of LDOTD on a total of 79.1 miles of newly constructed pavements are reported. Based on extensive tests and comparison of APPARE system with other alternatives, LDOTD has recently decided to adopt APPARE as its standard profilograph test procedure for quality control/acceptance of newly constructed pavement.

Report related to SHA Survey Questions: 2, and 8.

3.

Staigle, Rick; Ksaibati, Khaled; Adkins, Thomas; **Smoothness Effectiveness of Flexible Pavements.** University of Wyoming, and Wyoming Department of Transportation, A Draft submitted to the Transportation Research Board, 1996.

Abstract:

This research study was conducted at the University of Wyoming to examine if the initial roughness of a pavement section has any effects on its long-term performance. The statistical tests performed indicate that flexible pavements with low smoothness do stay smooth over time.

Report related to SHA Survey Questions: 2 and 6.

4.

Shuler, Scott; Horton, Stephen; **Development of a Rational Asphalt Pavement Smoothness Specification in Colorado.** Colorado Asphalt Pavement Association, and Colorado Department of Transportation, A draft submitted for the Transportation Research Board, 1996.

Abstract:

Colorado began development of a specification describing the smoothness of asphalt pavements in 1992. The specification is based on smoothness data collected using the California rolling Profilograph. The first projects using the smoothness specification were constructed in 1994. Significant changes in this version based on work in the 1994 were incorporated in the second version of the specification in 1995. The specification is unique since it uses 0.1-inch null band, half that of most states, discriminates between highway facility types, and uses both absolute value of smoothness and percentage of improvement criteria to control ride quality. The 1995 specification is still evolving since it contains a requirement for cold milling that will eventually be eliminated. The specification contains an incentive-disincentive clause to allow contractors to recoup investments made to improve smoothness quality. This clause has already paid dividends by improving ride quality after contractors purchase new or improved equipment and construction practices to achieve higher levels of smoothness.

Report related to SHA Survey Questions: 1, 2, 3, 4, and 9.

5.

Walls III, James; Grogg, Max G; Hallin, John P; **Interstate HPMS IRI Data Analysis.** Federal Highway Administration, Pavement Design and Rehabilitation Branch, January 1994.

Abstract:

The FHWA and SHA's are shifting their focus toward the important task of maintaining the Interstate pavement system at a performance level that meets the needs of the nation. Presently, the only nationwide source of current and historic interstate pavement condition is the data contained in the FHWA's Highway Performance Monitoring System (HPMS). Historically, the HPMS effort has collected sample pavement condition data in the traditional form of present serviceability ratings (PSR). In 1989, HPMS added the International roughness index (IRI) as an additional data element. This report analyzes the 1990 through 1992 Interstate HPMS IRI data to establish an understanding of current National and individual State Interstate pavement conditions and recent trends in pavement condition. The results of recent research are presented, which attempt to correlate the IRI data to PSR.

Report related to SHA Survey Questions: 2

6.

AASHTO Highway Subcommittee on Construction; **Rigid and Flexible Pavement Rideability Questionnaire.** November 1981.

Abstract:

The AASHTO Highway Subcommittee on construction developed and transmitted a rideability questionnaire to each of the member States to establish a current consensus of information on the use of rideability specifications. The questionnaire also included suggested rideability specifications for both rigid and flexible pavements. This report reflects the results and comments from the survey, including comments on the suggested pavement rideability specifications.

Report related to SHA Questions: 1, 2, 4, 5, and 6.

7.

FHWA / UMTRI Contract DTFH 61-929C00143; Interpretation of Road Roughness Data. June - August Report. 1994

Abstract:

The primary objective to this research is to develop guidelines on how to obtain useful information from road profiles. Of particular interest are relationships between longitudinal pavement profile and ride quality, pavement performance, dynamic loads, highway safety, and vehicle and cargo wear. The secondary research objective is to assist state profiler users in resolving unexplained sensitivities of profile measurements to speed, resolution, sampling interval, road properties, and other factors.

Report related to SHA Questions: 2

8.

Guide Specifications for Highway Construction, Division 500 - Rigid Pavement and Division 400 - Flexible Pavements.

Abstract:

The specification article for Division 500 - Rigid Pavement include general requirements for constructing a portland cement concrete pavement on a prepared subgrade or base course. The specification article for Division 400 - Flexible Pavements include general requirements that are applicable to all types of plant mix asphalt pavements irrespective of aggregate gradation, kind of asphalt or pavement use.

Related to SHA Survey Questions: 1, and 2.

9.

Scofield, Larry A, P.E.; Profilograph Limitations, Correlations and Calibration Criteria for Effective Performance-Based Specifications. NCHRP Project 20 - 7, Task 53, 1993.

Abstract:

The purpose of this study was to assess the state of the practice in the use of profilographs for measurement of pavement smoothness. The critical objectives were to evaluate the nature and extent of problems and to recommend research to accomplish solutions to these problems.

The study conducted a survey of the states and industry to identify problems and to determine the state of the art practice. A literature search was performed and a limited analysis of the automated profilograph filters conducted. The results of this study depict the state of the art practice through 1992.

Report related to 1, 2, 3, 4, 5, 6, 7, and 8.

10.

Hudson, W.R.; Dossey, Terry; Harrison, Rob; **End-Result Smoothness Specification for Acceptance of Asphalt Concrete Pavements.** 7th International Conference on Asphalt Pavements, 1991.

Abstract:

This paper documents the development and evaluation of end-result smoothness specifications for asphalt concrete pavements in Texas. Based on available equipment and prior studies, the California Profilograph was selected as the instrument for use in developing the specification. Because there are several types of California profilographs, the study team compared two instruments by two different manufactures. This paper presents the results of this comparison, along with a methodology for defining a recommended specification.

Report related to SHA Survey Questions: 2, 3 and 8.

11.

AASHTO; **Summary Results of the 1987 AASHTO Rideability Survey.** 1987.

Abstract:

The AASHTO Subcommittee developed and transmitted an updated questionnaire in January 1987. The main thrusts of the new questionnaire were to first distinguish between rideability specifications and bump specifications, secondly, an effort to determine the roughness measurement equipment was undertaken, and thirdly, determine the extent of the use of incentives and disincentives.

Report related to SHA Survey Questions: 2 and 7.

12.

FHWA; **401.03 Asphalt Concrete Specifications.**

Abstract:

There has been a large amount of information provided concerning the use and benefits of rideability specifications. This paper is to help engineers to in the field become more familiar with the various types of equipment available to enforce these specifications. The following information is provided to give an overview of the equipment characteristics, operational and calibration methods and costs.

Report related to SHA Survey Questions: 1, 2, 7 and 8.

13.

Kulakowski, Bohban; Wambold, James; **Development of Procedures for the Calibration of Profilographs, Final Report.** The Pennsylvania Transportation Institute. February 1989.

Abstract:

A review of current information concerning the methods and equipment for measuring the roughness of new pavements revealed that most states use rideability criteria to determine the quality of newly paved pavement. A full scale testing program investigated the basic roughness characteristics of new pavements, represented by power spectral density functions which were then used to generate average profile data. Road roughness measuring devices, including the CA, Rainhart, and Ames profilographs, profilometer, and Mays meter, were evaluated on the basis of frequency response, precision, repeatability, reliability, and ease of operation. Researchers sought to determine whether correlations can be established between the profilographs and other roughness measuring devices.

Report related to SHA Survey Questions: 1, 2, and 7.

14.

ATRC; **A Half Century with the California Profilograph.** Arizona Transportation Research Center. February 1992.

Abstract:

This study was performed to establish equipment and operator variability for mechanical and computerized CA profilographs. The historical development of the profilograph and the California test procedures and specifications were evaluated in relationship to today's incentive/disincentive specifications. Additionally, equipment parameters which influence test variability were reviewed.

Report related to SHA Survey Questions: 2 and 7.

15.

Omari, Al; Darter, Michael I.; **Relationships between IRI and PSR.** Department of Civil Engineering University of Illinois at Urbana-Champaign. September 1992.

Abstract:

This report documents the work accomplished on a study to develop relationships between the International Roughness Index (IRI) and Present Serviceability Rating (PSR) for pavement types included in the HPMS database. Relationship between IRI and PSR were analyzed for the state of Louisiana, Michigan, New Jersey, New Mexico, and Ohio which were found in the NCHRP Project 1-23 database, plus additional data from Indiana.

Report related to SHA Survey Questions: 2 and 7.

16.

Smith, Kelly L, Smith, Kurt D, Hoerner, Todd E, & Darter, Michael I, **On The Effect of Initial Pavement Smoothness** TRB Report 97-1146, December 1996

Abstract:

This paper examines the effect of initial pavement smoothness on the future smoothness and future life of both asphalt concrete (AC) and portland cement concrete (PCC), as well as AC overlays of existing AC and PCC pavements. It is shown that initial pavement smoothness has significant effect on the future smoothness of the pavement in 80 percent of new construction (both AC and PCC pavements) and in 70 percent of AC overlay construction. Furthermore, using two different analysis techniques, it is illustrated that added pavement life can be obtained by achieving higher levels of initial smoothness. Combined results of both roughness model and pavement failure analyses indicate at least a 9 percent increase in life corresponding to a 25 percent increase in smoothness from target profile index (PI) values of 7 and 5 in/mi (0.11 and 0.08 m/km) for concrete and asphalt pavements, respectively.

Report related to SHA Survey Questions: 5

17.

Weed, Richard M, **A Sure Ride,** Civil Engineering, February 1997.

Abstract:

In 1992, the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO) and several industry associations joined forces to form a unique partnership called the National Quality Initiative (NQI). This program was designed to raise the level of consciousness on quality issues in the public sector. One objective of this program is to provide guidance on practical and effective procedures that can be implemented to ensure that the level of quality designated into the plans and specifications is actually achieved in the construction product. Part of this effort was the development and distribution of a software package consisting of several interactive programs for use on a personal computer.

Report related to SHA Survey Questions: 4, 5, 6, and 7.

18.

Cumbaa, Steven L, **Using the International Roughness Index for Profilograph Trace Reduction,** Transportation Research Record 1536, pgs 90 - 93, 1996.

Abstract:

Current Louisiana acceptance specifications for 100 percent payment require Profile Indexes (PIs) completed pavement surface to as low as 3.0 in/mi for flexible pavements and 6.0 in/mi for rigid pavements. These acceptance specification are currently among the most stringent in the United States. Requiring an acceptance PI value of less than 7.0 in/mi when using the California-style profilograph and the 0.2 in blanking band is unacceptable unless the blanking-band is eliminated from the procedure. Louisiana's efforts to replace the blanking-band evaluation procedure with a procedure that inputs the profile trace into the quarter-car-based International Roughness Index (IRI) model are present. The key step in this process is the scanning and digitization of the profilogram before determining the IRI based on the filtered profile trace. A much better correlation exists between the rideability of the finished surface and the profilograph IRI than that of the profilograph PI. New profiliograph IRI specifications are recommended to replace the existing PI specifications.

Report related to SHA Survey Questions: 2 and 7.

Appendix 9

References

REFERENCES

1. Janoff, Michael S, "Pavement Smoothness" IS 111 National Asphalt Pavement Association (NAPA), Lanham, MD.

2. Sayers, Michael W, Gillespie, Thomas D, & Paterson, William D.O, "Guidelines for Conducting and Calibrating Road Roughness Measurements" World Bank Technical Paper Number 46, The World Bank, Washington, D.C., 1986.

3. ERES Consultants, Inc, "Smoothness Specifications for Pavements" NCHRP Project 1-31, Technical Memorandum, November, 1994.

4. Collura, John, & El-Korchi, Tahar, "A Proposal To Conduct a Study entitled Guidelines for Ride Quality Acceptance of Pavements", University of Massachusetts and Worcester Polytechnic Institute Transportation Departments, 1995.

5. Hudson, W. R., "Road Roughness: Its Elements and Measurements", Transportation Research Record 836, Transportation Research Board, National Research Council, Washington D.C., 1981, pp. 1-7.

6. Hegmon, Rudolph R. "A Close Look at Road Surfaces", Public Roads, U.S. Department of Transportation, Federal Highway Administration, Vol. 57, No. 1, Washington D.C., Summer 1993.

7. Sayers, M., & Gillespie, T. D., "Better Method for Measuring Pavement Roughness with Road Meters", Transportation Research Record 836, Transportation Research Board, National Research Council, Washington D. C., 1981, pp. 35 - 41.

8. Yoder, E. J, & Milhous, R. T, "Comparisons of Different Methods of Measuring Pavement Conditions", National Cooperative Highway Research Program, Washington, D.C., 1964.

9. Gulen, Sedat, Woods, Robert, Weaver, John, & Anderson, Virgil L., "Correlation of Present Serviceability Ratings with International Roughness Index", Transportation Research Record 1435, Transportation Research Board, National Research Council, Washington D.C., 1994.

10. Gramling, W. L. "Current Practices in Determining Pavement Condition", Synthesis of Highway Practice 203, National Cooperative Highway Research Program, Washington, D.C., 1994.

11. Massachusetts Turnpike Authority, Specifications for Bituminous Concrete Paving, Boston, Massachusetts, 1996

12. Al-Omari, Bashar & Darter Michael I., "Relationships Between International Roughness Index and Present Serviceability Rating", Transportation Research Record 1435, Transportation Research Board, National Research Council, Washington D.C., 1994.

13. Darlington, John, "Road Profile - The Bottom Line", Pavement Newsletter, U.S. Department of Transportation, Federal Highway Administration, Issue 18, Washington D.C., Spring 1991.

14. Woodstrom, J.H., "Measurements, Specifications, and Achievement of Smoothness for Pavement Construction", Synthesis of Highway Practice 167, National Cooperative Highway Research Program, Washington, D.C., 1990.

15. Wambold, J. C., Defrain, L. E., Hegmon, R. R.,McGhee, K., Reichert, J. & Spangler, E. B., "State of the Art Measurement and Analysis of Road Roughness", Transportation Research Record 836, Transportation Research Board, National Research Council, Washington D. C., 1981, pp. 21 - 29.

16. Federal Highway Department, "Appendix J" FHWA Order M 5600.1B, Washington D. C August 1993.

17. Manual for Profile Measurement: Operational Field Guidelines, Strategic Highway Research Program, National Research Council Washington D.C., 1994.

18. Ksaibati, K, Asnani, S, & Adkins, T. M., "Factors Affecting Repeatability of Pavement Longitudinal Profile Measurements", Transportation Research Record 1410, Transportation Research Board, National Research Council, Washington D.C. 1993. pp. 59-66.

19. Lu, Jian, Hudson, W. Ronald, & Bertrand, Carl, Evaluation of Roughness System of Automatic Road Analyze, Transportation Research Record 1435, Transportation Research Board, National Research Council, Washington D.C. 1994.

20. Walker, Roger S. & Lin, Hong-Tsung, Profilograph Correlation Study with Present Serviceability Index, Transportation Research Record n 1196 1988. p 257-275.

21. Constructing Smooth Concrete Pavements: Technical Bulletin 006.0-C, American Concrete Paving Association, Arlington Heights, Illinois, 1990.

22. Cumbaa, Steven L., Using the International Roughness Index for Profile Trace Reduction, Transportation Research Record 1536, Transportation Research Board, National Research Council, Washington D.C. 1996

23. Benson, K.R.; Elkins, G.E. Uddin, W. & Hudson, W.R. Comparison of Methods and Equipment to Conduct Pavement Distress Surveys, Transportation Research Record n 1196 1988. p 40-50.

24. Hardenbergh, W. The Secret to Quality Paving is No Secret, Training Video, Catepillar Paving Products, Inc., Dekalb, Illinois, 1994

25. Kulakowski, Bohdan T, & Wambold, James C, "Development of Procedures for the Calibration of Profilographs", The Pennsylvania Transportation Institute. February, 1989.

26. Carmichael, R. F, Moser, L. O, & Hudson, W.R, "Measurement of Pavement Smoothness for Construction Quality Control" Arizona Department of Transportation, February 1992.

27. Staigle R, Ksaibati K, & Adknis T, "Smoothness Effectiveness of Flexible Pavements" TRB Report 96-0145, University of Wyoming, August 1995.

28. Smith, Kelly L, Smith, Kurt D, Hoerner, Todd E, & Darter, Michael I, "On The Effect of Initial Pavement Smoothness" TRB Report 97-1146, December 1996.

29. Shuler, Scott, & Horton, Stephen, "Development of a Rational Asphalt Pavement Smoothness Specification in Colorado" TRB Report 96-0342, Colorado Department of Transportation, 1995.