DEVELOPMENT AND APPLICATION OF A STATISTICAL QUALITY ASSESSMENT METHOD FOR DENSE-GRADED MIXES

Final Report

SPR #323

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by

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16. Abstract

This report describes the development of the statistical quality assessment method and the procedure for mapping the measures obtained from the quality assessment method to a composite pay factor. The application to dense-graded mixes is demonstrated with an example. This report also describes the development of a smoothness specification based on the IRI. A draft smoothness specification is also included in the appendices.

The research team developed a methodology to measure the quality of dense-graded asphalt mixes based on a statistical function called a loss function. Various formulations of the loss function are routinely used in manufacturing to provide quality control/quality assurance measures. The methodology developed for this project provides a pay incentive to contractors that exceed quality expectations, and a penalty to those who fall short of quality expectations. The methodology encourages contractors to produce asphalt mixes that are consistent with specifications with minimum variability.

Two principal specification-related products were produced. The first product allows ODOT to statistically judge the HMA quality using the loss function. Second, data analyses showed that project smoothness, as measured by IRI, could be incorporated into an ODOT specification, but only in the form of percent improvement in ride over the existing roadway.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

DEVELOPMENT AND APPLICATION OF A STATISTICAL QUALITY ASSESSMENT METHOD FOR DENSE-GRADED MIXES

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1.0 INTRODUCTION

The purpose of this research project, as it evolved through interaction between the research team and the Technical Advisory Committee, resulted in three primary deliverables.

- Identification of factors that can be measured during hot mix asphalt (HMA) production and placement that relate to performance, and designate them as the items upon which quality price adjustments will be based.
- Development of a statistical methodology that incorporates deviation from target, as well as variability, to evaluate the quality of HMA.
- Development of a smoothness (ride) specification based on the International Roughness Index (IRI).

The research team developed a methodology to measure the quality of dense-graded asphalt mixes based on a statistical function called a loss function. Various formulations of the loss function are routinely used in manufacturing to provide quality control/quality assurance measures. The methodology developed for this project provides a pay incentive to contractors that exceed quality expectations, and a penalty to those who fall short of quality expectations. The methodology encourages contractors to produce asphalt mixes that are consistent with specifications with minimum variability.

This report describes the development of the statistical quality assessment method and the procedure for mapping the measures obtained from the quality assessment method to a composite pay factor. The application to dense-graded mixes is demonstrated with an example. This report also describes the development of a smoothness specification based on the IRI. A draft smoothness specification is also included in the appendices. A separate report describing the process for identifying factors best related to performance, as well as the philosophy behind the development of a draft revised specification for HMA, in Oregon, will be published in conjunction with completion of the final revised draft specification during the fall of 2004.

2.0 STATE OF THE PRACTICE

The use of contractors to construct public roads, and specifications to control that construction, date from at least the 1850s. Method specifications were described as far back as the mid-19th century (*Gillespie 1849*). Construction specifications have evolved from method specifications, which dictate contractor process, to end-product specifications, which measure material properties that are thought to relate to performance. The next step, performance-related specifications, will directly relate expected pavement performance to measured mix properties. The evolution of construction specifications in the United States is well documented in numerous National Cooperative Highway Research Program (NCHRP) Syntheses. As shown in Table 2.1, these syntheses cover approximately the last 25 years.

Table 2.1: NCHRP syntheses related to specifications

Synthesis Number	NCHRP Title
38	Statistically Oriented End-Result Specifications (1976)
65	Quality Assurance (1979)
102	Material Certification and Material-Certification Effectiveness (1983)
120	Professional Resource Management and Forecasting (1985)
145	Staffing Considerations in Construction Engineering Management (1989)
146	Use of Consultants for Construction Engineering and Inspection (1989)
163	Innovative Strategies for Upgrading Personnel in State Transportation Departments (1994)
195	Use of Warranties in Road Construction (1994)
212	Performance Related Specifications for Highway Construction and Rehabilitation (1995)
232	Variability in Highway Pavement Construction (1996)
263	State DOT Management Techniques for Materials and Construction Acceptance (1998)

2.1 BRIEF HISTORY OF SPECIFICATIONS

The most complete summary of the development of highway construction specification is available in NCHRP Synthesis 212 (*Chamberlin 1995*). The very thorough documentation contained in that report will not be repeated here. There are some critical events impacting the development of specifications that are worth summarizing.

Though not the first analysis of variability of highway materials and construction, the AASHTO Road Test (1956-1962) provided the most comprehensive and well-documented measurement of variability. The Road Test specifications were intended to represent specifications typical of those used on a large highway construction program (*Carey and Shook 1966*). Yet despite considerable effort, Carey and Shook concluded:

> Briefly summarizing, we want to show that with many more well-trained inspectors than could economically be used in normal construction, with high-speed testing techniques, with a large-scale materials laboratory on site, with the ability to control in detail the contractor's construction procedures, with a highly competent and cooperative contractor who was well paid for everything he was required to do, and the eyes of the highway fraternity on the back of our necks, we were still unable to meet the specifications of many of the construction items within a country mile.

The magnitude of the measured variation at the Road Test surprised many highway engineers (*NCHRP Syntheses 38 and 65*). Carey and Shook went on to say:

> Sampling plans now being used are not adequate for estimating the true characteristics of materials or construction items for which the specifications are written, and certainly cannot guarantee 100 percent compliance to the specification limits.

In addition to the revelation that construction variations were higher than expected, several high-profile highway failures occurred about the time of the AASHO Road Test. The failures resulted in the formation of a U.S. Congressional Committee, and ultimately Congress threatened to pass laws making it a federal offense to "knowingly incorporate" any non-complying materials in highway work (*NCHRP Synthesis 38*). Changes in the traditional acceptance procedures and a higher level of accountability were required, given the documented AASHO Road Test construction variability and Congress' threat to become involved in construction specification (*Chamberlin 1995*).

The events of the 1960s led to alternate methods of measuring the characteristics of materials and construction (M&C) items and their compliance with specification limits. These efforts eventually were termed "statistical quality assurance (SQA)" or "end result specification (ERS)." These alternate methods recognized the inherent variability of M&C variables and acknowledged that 100 percent compliance was impractical.

The development of the new standards led to increased communication between the contractor and the agency regarding the feasibility of 1) contractors assuming more responsibility for quality control, and 2) highway agencies judging acceptance on the characteristics of the end product (e.g., end result). The standards ultimately distinguished between the responsibilities of the vendor (for quality control) and the purchaser (for specification and quality assurance). One consequence of this process was that more rapid testing methods were developed (*Halstead 1993*).

The elements of an ideal quality assurance system were described by Chamberlin in 1968 and are shown in Figure 2.1. Although not specifically described in Chamberlin's model, both statistically based sampling and acceptance criteria are essential to a successful specification.

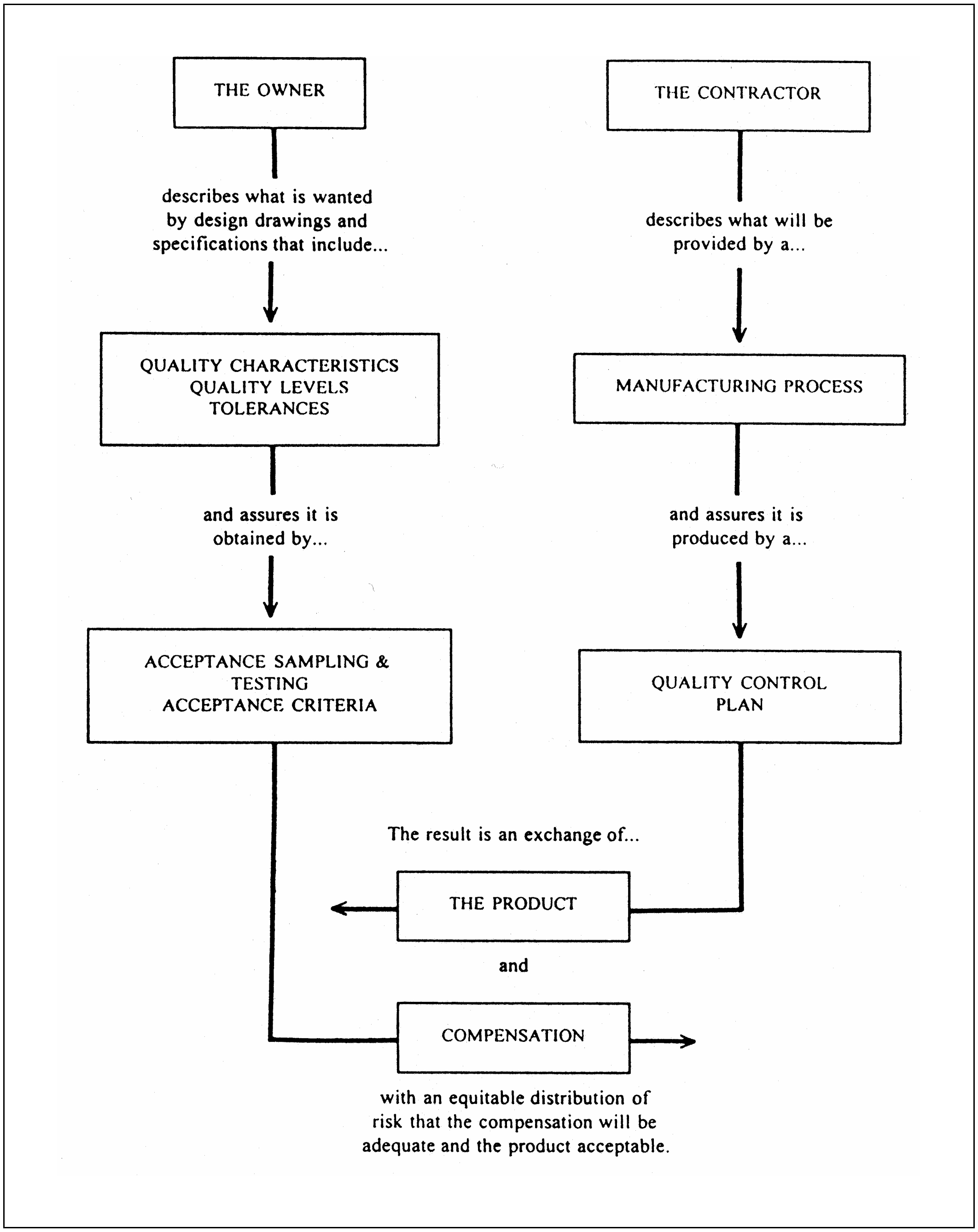

Figure 2.1: Elements of an ideal quality assurance system (after *Chamberlin 1968*)

Many SQA techniques were adopted from the procurement procedures developed by the U.S. Department of Defense (*Military Standard 414 1957*). Early implementations of end result specifications only included disincentives. These adjustments allowed the acceptance of materials deficient in terms of specification, but not without value, as an alternative to removal. Most of the early disincentives were related to the loss of pavement performance through the judgment of agency engineers.

The quality assurance system shown in Figure 2.1 implies that compensation will be commensurate with the acceptability of the product. Incentives as well as disincentives should be a part of the ideal quality assurance system.

Full implementation of statistical end result specifications proceeded slowly even though the applicable statistical sampling and decision theory had been fully developed for highway construction by the early 1970s (*Chamberlin 1995*). In particular, agencies were slow to implement incentives. This was due, in part, to the reasons cited by Chamberlin: 1) the inability to identify or measure the essential performance-related characteristics of the end product; 2) the inability to quantify substantial compliance and to determine price adjustment factors that relate to reduced or enhanced value; and 3) the uncertainty as to value to be gained from the cost of implementing statistically based end result specifications (*Chamberlin 1995*).

Chamberlin suggests that while the use of end-result specifications may have improved compliance and provided improved evidence of compliance in them, they do not guarantee improved performance. Improved performance relies on understanding the relationship between factors controlled during construction and the performance of the finished product. As will be discussed below, these relationships are only just beginning to emerge.

2.2 RECENT DEVELOPMENTS

Despite the fact that definitive performance relationships are not yet available for most factors controllable during construction, the development of quality assurance specifications continues. In fact there has been a call for a national policy for the management of quality (*Afferton, et al 1992*). Several recent surveys suggest that many agencies have implemented some form of quality assurance specifications, many with some form of incentive/disincentive pay schedule.

2.2.1 Current Practice

NCHRP Synthesis 232 (*Hughes 1996*) reports that 42 of 48 respondents to a survey stated that they included incentive or disincentive in their pay schedule, while four did not. Asphalt concrete material or construction factors for which incentives or disincentives are used are shown in Table 2.2. Disincentives were used more frequently than incentives except for ride quality. At the time of this survey, volumetric properties were not routinely used on pay factor calculation.

Table 2.2: DOT use of incentive and disincentive pay schedules (after *Hughes 1996*)

Material Property or Construction Factor	Incentive	Disincentive
Aggregate Gradation	6	21
Asphalt Content	8	25
Volumetric Properties	3	10
Compaction	14	31
Thickness	5	26
Ride Quality	21	25

In NCHRP Synthesis 263 (*Smith 1998*), 35 of 41 survey respondents indicated that they included some form of incentive/disincentive as part of their materials and construction acceptance process. Thirty-one of the 35 agencies reported some form of incentive/disincentive for hot-mix asphalt as shown in Table 2.3. Acceptance specifications that include smoothness are the most common (21 of 31) followed by density specifications (14 of 31). Specification incentives or disincentives associated with thickness are the least common. The survey was sent to Departments of Transportation in September 1996. Detailed information on the characteristics of these specifications was not available.

Table 2.3: HMA specification attributes with incentive/disincentive factors (after *Smith 1998*)

State	HMA Density	HMA Mix	Asphalt Content	Aggregate Gradation	HMA Thickness	Smoothness
Alabama	✓	✓	✓			✓
Alaska	✓			✓		
Arkansas		✓				✓
Arizona						✓
Connecticut	✓			✓		
California	✓	✓	✓	✓		
Illinois					✓	✓
Iowa						✓
Maine	✓		✓	✓		
Maryland	✓		✓	✓		✓
Michigan	✓					✓
Minnesota						✓
Missouri						✓
Nebraska						✓
New Hampshire		✓				
New Jersey		✓				✓
New Mexico	✓	✓	✓	✓		
Nevada		✓				
North Carolina						✓
North Dakota						✓
Ohio						✓
Oklahoma	✓		✓	✓		✓
Pennsylvania	✓		✓		✓	✓
South Carolina	✓				✓ (base)	✓
Tennessee			✓	✓		✓
Texas		✓				✓
Utah	✓		✓	✓		
Vermont		✓				
Washington	✓		✓	✓		
Wisconsin						✓
Wyoming	✓			✓		✓
Totals	**14**	**9**	**10**	**11**	**3**	**21**

Mahoney and Backus reported the results of a survey conducted in April 1999 (*Mahoney and Backus 1999*). Although fewer states responded to the questionnaire than to the Synthesis 263 questionnaire, the results provide additional information on SQA specifications in use and under development. Twelve responses were received from 50 states surveyed. Quality control and assurance results are summarized in Table 2.4. Most agencies require contractor QC measures on mix process (i.e., binder content, gradation) or construction (i.e., density) elements that are amenable to rapid testing/reporting. Volumetrics (i.e., VMT, VMA) are also included by many agencies. Quality assurance measures generally follow the QC program requirements, with 6 of the 12 states requiring or developing a smoothness requirement.

Table 2.4: 1999 specification information (after *Mahoney 1999*)

State	Contractor QC Requirements				Agency QA Requirements				
	Aggregate Gradation	Binder Content	In-Place Density	Volumetrics	Aggregate Gradation	Binder Content	In-Place Density	Smooth-ness	Volumetrics
AR	✓	✓	✓	VMT, VMA	✓	✓	✓	✓	VMT, VMA
FL	✓	✓	✓	VMT	✓	✓	✓	✓	VMT
IN	✓	✓	✓	VMT, VMA	✓	✓	✓	✓	
KY	✓	✓	✓	VMT, VMA		✓	✓		VMT, VMA
OH	✓	✓	✓[1]		✓	✓	✓		VMT, VMA
OR	✓	✓	✓	VMT, VMA, VFA[2]	✓	✓	✓	✓	VMT, VMA, VFA
RI					✓	✓	✓		
SC	✓	✓				✓	✓		VMT, VMA
WA					✓	✓	✓		
WI	✓	✓	✓	VMT	✓	✓	✓	✓	VMT
WY	✓		✓	[3]	✓	✓	✓	[4]	

Notes: [1] Contractor option
[2] Also smoothness, moisture in mix
[3] Mix verification during startup, then once per 20,000 tons
[4] Under development

The 1999 survey reported by Mahoney and Backus also included several other questions on QC/QA requirements (*Mahoney and Backus 1999*). The following statements summarize the responses of the states reporting QC/QA programs:

- Almost all agencies reported that the QC program increased the quality of work performed by the contractor.
- The “typical” QA spec has been in service for about 12 years. Most states revise their QA program annually or biannually.
- Only one state (IN) reported the statistical risk to the seller (α) or buyer (β).
- One-third of the states (4) reported that no incentives were allowed; the reminder reported maximum incentives ranged from 105 to 112 percent. Of these states, the average incentive was 103 percent.
- Of the states allowing incentives, most reported that the percentage of jobs receiving bonuses ranged from 60 to 100 (average 85 percent). One state (AR) reported that only 20 percent received bonuses.
- Of the ten states responding to the question, eight reported that virtually no lots were rejected during a typically year. Two reported that “some” (between 10 and 50 percent) lots were rejected.
- Quality assurance lot sizes ranged from 750 tons to 5,000 tons. Some states varied lot size with the attribute tested or use of the material (e.g., base or surface course).

In addition to collecting information on the general use and nature of QC/QA specifications, the survey by Mahoney and Backus asked for copies of current specifications allowing direct comparisons of some elements. Binder content tolerances and density limits are shown in Table 2.5. Other information taken from these states’ specifications are reported in the Mahoney report. The report notes that states have developed a wide array of quality requirements and specifications despite the fact that in each case the end product serves essentially the same function (*Mahoney and Backus 1999*).

Table 2.5: Binder content and density requirements

State	Binder content tolerance	Percent Density Requirements [1]
Florida	+/- 0.55%	96 [2]
Indiana	+/- 0.30 to +/- 0.70% [3]	91.5
Kentucky	+/- 0.50%	96 [2]
Minnesota	+/- 0.4%	91.5
Ohio	+/- 0.6%	92
Oregon	+/- 0.5%	92
Washington	+/- 0.5%	91
Wyoming	+/- 0.25%	92

Notes: [1] Percent of maximum specific gravity unless otherwise noted
[2] Percent of valid control strip density
[3] Depends on number of samples taken

Most states reported using the quality level approach to determine the percent defective or percent within limits (PD and PWL, respectively). The quality level approach is currently used by ODOT. Alternate approaches are discussed below.

2.2.2 Conformal Index

An alternative to the standard deviation approach to specifications is the statistic referred to as the conformal index. The conformal index (CI) is a measure of variation like the standard deviation. However, the comparator is a quality level target (i.e., JMF asphalt content) rather than the mean as is the case for the standard deviation. In other words, the standard deviation is a measure of precision, and the CI is a measure of exactness (accuracy) of degree of conformance with the target. In equation form,

$$\sigma = \frac{\sqrt{\sum \left(x - \bar{x}\right)^2}}{(n-1)} \qquad CI = \frac{\sqrt{\sum (x - T)^2}}{n} \tag{2-1}$$

Where T = a target value (JMF) such as design thickness, density, etc.

The attractiveness of the conformal index in QC/QA specifications is that it focuses attention on a target value, and it is this target value that defines the quality level. The CI can be used with either percent within limits (PWL) or percent defective (PD) specifications. Additionally, because the CI normalizes to a target value, direct comparisons may be made by the contractor as to the magnitude of variation about the target for QC purposes; comparisons by the agency of the contractor's conformance to the specification for acceptance purposes; and, if desired, comparisons of performance between contractors, projects, etc. (*Cominsky, et al. 1998*). Tolerance limits for a conformal index approach are shown in the section on Superpave mixes.

Weed examined three measures of variability – average absolute deviation (AAD), conformal index (CI) and percent defective (PD) – to determine the ability of each to discriminate between different distributions (*Weed 1999*). Three hypothetical scenarios were developed, one for each measure of variability as shown in Figure 2.2.

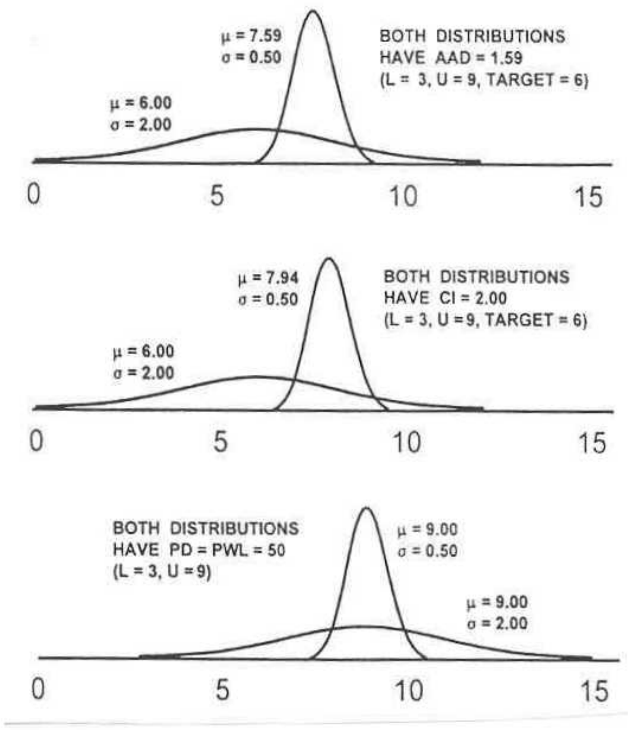

Figure 2.2: Potential weaknesses of common statistical measures of quality (*Weed 1999*)

The figure shows that none of the quality measures are able to distinguish between distributions that would be expected to produce markedly different levels of performance.

Both AAD and CI calculations are based on a target value (usually midway between the upper and lower specification limits). This approach is well suited to use with two-sided specification limits but not well suited to use with a one-sided specification limit for which a single target cannot be defined. Overlay thickness would be one example of a one-sided limit that would not be suited for use with the conformal index.

Weed also points out that the traditional PD approach, and its complement, percent within limits (PWL), have drawbacks when used with one-sided limits. For PWL values above 50, a decrease in standard deviation (with no change in the mean) cause the PWL to increase. However for PWL values less than 50, just the opposite effect occurs. Therefore, unless performance is independent of variability, there could be inconsistency in acceptance procedures particularly as the PWL approaches 50 percent. The alternate approach proposed by Weed is described below.

A different means of incorporating mean and standard deviation into specifications is presented by Weed (*1999*). This approach avoids the problems of the traditional PWL (PD) approach as well as those of the conformal index and average absolute difference noted above. Weed presents the following general forms of pay equations:

Single Lower Limit:

$$PF = 100 + A\left[\frac{\left\{\bar{x} - B(s) - LIMIT\right\}}{LIMIT}\right] \tag{2-2}$$

Single Upper Limit:

$$PF = 100 + A\left[\frac{\left\{LIMIT - \bar{x} - B(s)\right\}}{LIMIT}\right] \tag{2-3}$$

Double Limits:

$$PF = PF_{MAX} - A\left[\frac{\left\{ABS(\bar{x} - TARGET) + B(s)\right\}}{TARGET}\right] \tag{2-4}$$

Where

PF = pay factor (percent),

PF_{MAX} = maximum pay factor for double-limit specification,

A, B = equation coefficients,

$\bar{x}$ = sample average,

s = sample standard deviation,

LIMIT = limit for single-limit specification,

TARGET = target value for double-limit specification,

ABS = absolute value operator.

Equations of this form avoid some of the weaknesses noted for the CI, AAD, and traditional approach. The coefficients A and B would be determined based on the performance of the pavement as affected by the measure under question. The coefficient B is dependent on the sample size since the standard deviation is not an unbiased estimate of the population standard deviation.

Equation 2-2 provides for higher pay factors as the sample mean moves further above a single specification limit and as the standard deviation becomes smaller. Similarly Equation 2-3 yields higher pay factors as the sample mean moves farther below the upper specification limit. Equation 2-4 provides higher pay factors as the sample average approaches the target and as the standard deviation decreases. Equations 2-2 and 2-3 may add or subtract from the constant pay factor of 100. Equation 2-4 could pay incentives up to a maximum of PF_{MAX}. All the pay factors could be limited to some agency-selected maximum (i.e., 105).

Weed also provides for greater flexibility by applying exponents to the terms shown in Equations 2-2 through 2-4. This refinement (shown in Equations 2-5 through 2-7) may be necessary if it were found that performance declined increasingly rapidly as the mean shifts or the standard deviation increases.

Single Lower Limit:

$$PF = 100 + A\left(\frac{\bar{x} - LIMIT}{LIMIT}\right)^{C} - B\left(\frac{s}{LIMIT}\right)^{D} \qquad \textbf{(2-5)}$$

Single Upper Limit:

$$PF = 100 + A\left(\frac{LIMIT - \bar{x}}{LIMIT}\right)^{C} - B\left(\frac{s}{LIMIT}\right)^{D} \qquad \textbf{(2-6)}$$

Double Limits:

$$PF = PF_{MAX} - A\left(\frac{ABS(\bar{x} - TARGET)}{TARGET}\right)^{C} - B\left(\frac{s}{TARGET}\right)^{D} \qquad \textbf{(2-7)}$$

The paper (*Weed 1999*) provides comparisons between the traditional and proposed approaches for both single and double-sided specifications.

2.2.3 Composite Pay Factors

The use of composite pay factors is not new. Many agencies compute a composite pay factor by first calculating individual pay factors (PF) and then combining these using a weighting scheme. The weighting often follows a linear format such as that currently used by Oregon. The magnitude of specific weighting factors is selected using engineering experience, laboratory or field performance data, design equations or some combination of these elements.
Currently Oregon DOT includes the constituents shown in Table 2.6 in their HMA price adjustments.

Table 2.6: AC price adjustment factors (after *ODOT 2002*)

Constituent	Weighting Factor, f
All aggregates passing 37.5, 31.5, 25.0, 19.0 and 12.5 mm sieves	1
All aggregates passing 4.75 mm	5
All aggregates passing 2.36 mm	5
All aggregates passing 600 µm	3
Aggregate passing 75 µm sieve	10
Asphalt	26
Moisture content	8
Compaction (density)	40

The composite pay factor is based on the sum of the individually computed pay factors times the appropriate weighting factors divided by the sum of all weighting factors with an upper limit of 105. As can be seen, approximately 25 percent of the composite pay factor is based on aggregate gradation control. Although the specific weighting factors and constituents vary from state to state, the basic format currently used by ODOT is in use in many other states.

Weed (*2000*) proposed the introduction of unique composite pay factors based on the idea that the interaction among individual pay factor constituents should not be ignored. For example, an overlay placed with low asphalt content and low field density is more likely to fail early than an overlay placed with adequate asphalt at low field density. Weed contends that current weighting schemes do not take this interaction into account. A simple example taken from Weed (*2000*) illustrates the concept.

Assume that only air voids and pavement thickness are to be included as pay factors. Under the traditional approach, the rejectable quality level (RQL) might be set at 75 percent defective (PD) for both constituents. Consider the three scenarios shown in Table 2.7. It can be seen that although Case 3 is clearly the worst case, it does not trigger the RQL provision. Weed used a combination of expert opinion and pavement life modeling to arrive at a curve that separates acceptable from rejectable quality work. Further refinement of this equation allowed the development of a composite pay factor of the form:

$$PD^* = 0.807 PD_{voids} + 0.669 PD_{thick} - 0.00476 PD_{voids} PD_{thick} \qquad \textbf{(2-8)}$$

A family of curves developed from this equation is shown in Figure 2.3. A given project with 10 percent defective on both thickness and air voids would have a composite percent defective, PD*, of 14 percent. Similarly, a project with 50 percent defective on both thickness and air voids would have a PD* equal to 62 percent.

Table 2.7: Example of an inconsistent rejection provision (after *Weed 2000*)

Case	Air Voids	Thickness	Rejectable?
1	PD = 10	PD = 75 (RQL)	Yes
2	PD = 75 (RQL)	PD = 10	Yes
3	PD = 74	PD = 74	No

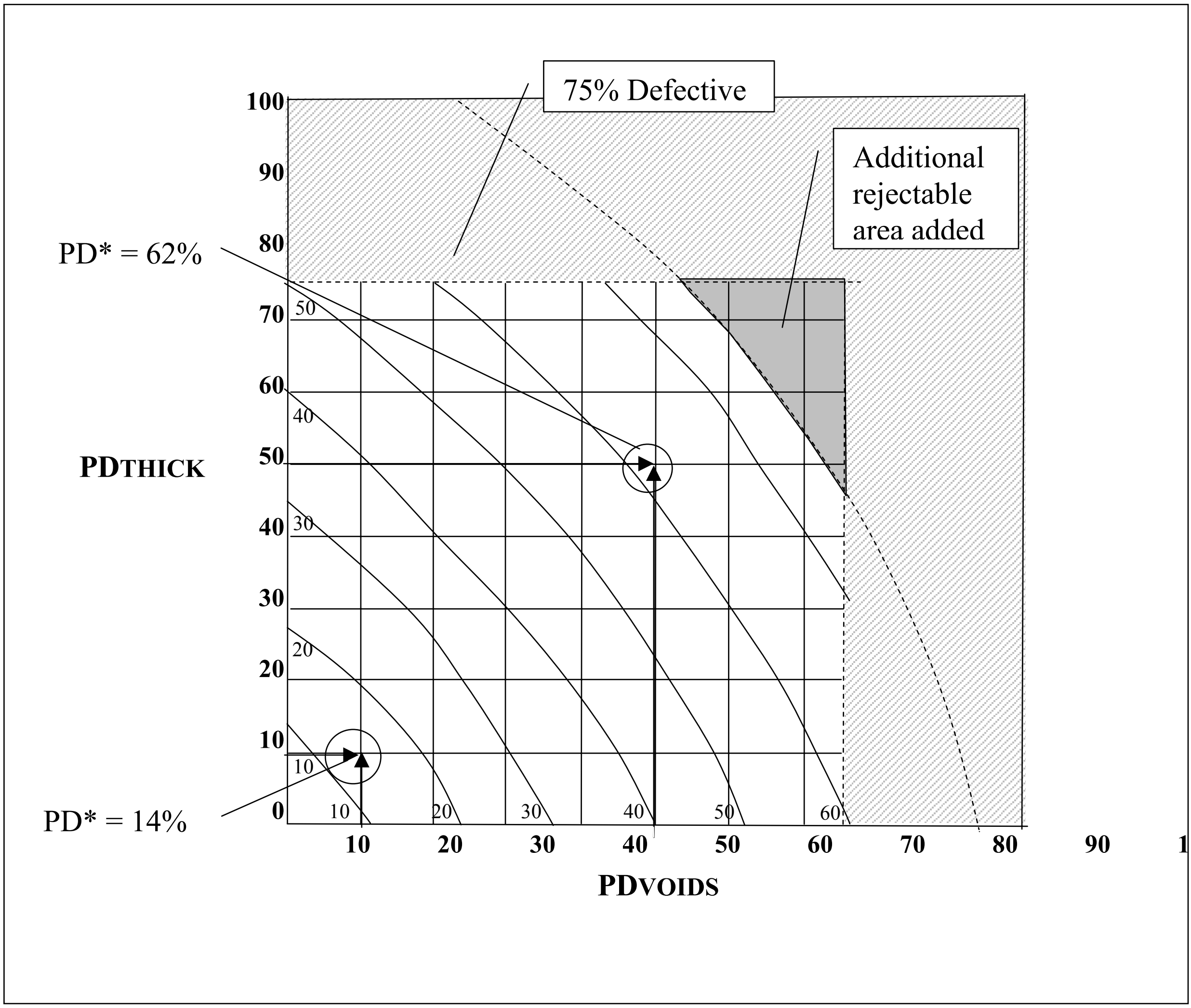

Figure 2.3: Interaction among pay factor constituents (*Weed 2000*)

Additional examination of Figure 2.3 shows that even if an agency's specification allowed rejection of the lot based on any one parameter reaching the RQL (i.e., voids = 75% defective), Weed's approach identifies combinations of parameters that may result in early failures (see the shaded area in Figure 2.3).

This approach is fairly easily implemented when only two or three parameters make up the composite percent defective. The development is considerably more complicated when a fourth or fifth term is added to the equation. Furthermore the extension from a composite percent defective calculation to a composite pay factor relies on the predicted pavement life for a variety of individual percent defective constituents. Given the status of currently available pavement performance prediction models, this extension is difficult.

2.2.4 Performance Related Specifications

Performance-related specifications bring to mind different things to different people, so a set of common definitions is needed. These definitions and associated comments were taken from NCHRP Synthesis 212 (*Chamberlin 1995*).

> A *performance specification* describes how the finished product performs over time. These specifications are not applicable to highway components because the technology is not sufficiently advanced.

The basis for these specifications may result from the Long-Term Pavement Performance project coupled with new tests. The results of these tests would directly relate to the performance of the pavement rather than some mix property.

> *Performance-based specifications* describe desired levels of fundamental engineering properties that are predictors of performance and appear in primary performance prediction relationships. These include properties such as resilient modulus and fatigue that are not amenable to timely acceptance testing.

Performance-based specifications are intended to improve existing levels of quality by focusing on performance properties. Some of the measured materials and construction characteristics cannot be reported to the contractor in a timely manner, precluding adjustments to the construction process.

> A *performance-related specification* (PRS) describes the desired level of material and construction factors that have been found to correlate with fundamental engineering properties that predict performance. These factors are amenable to acceptance testing at the time of construction.

Performance-related specifications are intended to identify the level of quality providing the best balance between cost and performance. Common material factors included in performance-related specifications included air voids, asphalt content, etc.

Presently, the use of performance-related specifications in this country is limited. Chamberlin reported in 1995 that although several federal and state projects were underway, only New Jersey had implemented performance-related specifications and only for PCC and PCC pavements. Subsequent to Chamberlin's report, several projects have worked to develop PRS for use with asphalt concrete.

NCHRP and FHWA funded a five-year study (Westrack) to develop performance-related specifications (PRS) for asphalt concrete. The study was completed February 1, 2000. Initial results of the study were presented during the 2000 TRB meeting at a special one-half day conference. To date, the study has developed PRS based on volumetric factors only. Eventually the Westrack PRS are expected to include elements based on Superpave test results such as those from the SST and IDT.

2.3 MIX SPECIFIC SPECIFICATIONS

This project is focused on dense-graded mixtures. Non-traditional dense-graded mixtures such as stone matrix asphalt (SMA) and Superpave mixtures are therefore included within the scope of this project. A transition to Superpave mixes is underway in Oregon, and the use of SMA mixes is increasing. Currently available practice for acceptance of these mixes is described below.

The current ODOT specifications may be accessed at the following internet site: www.odot.state.or.us/tsspecs/index.htm.

2.3.1 Superpave Mixes

A NCHRP report (*Cominsky, et al. 1998*) provides guidance on the use of quality control and quality acceptance specifications with Superpave mixes. The report emphasizes that the contractor QC plan is essential to successful Superpave projects. Not all of the recommended elements of contractor quality control will be repeated here. Although the report provides excellent guidance on the development and use of control and acceptance procedures, recommendations on pay factors are not included.

Cominsky, et al. (*1998*) recommended a quality acceptance plan that is similar in structure to that currently used by ODOT. The plan determines the total percent within limits (PWL) by first calculating the upper and lower quality indexes (levels). These values are used to estimate the percent within the upper or lower specification limits using tabular values similar to the FHWA tables. The PWL is equal to the sum of the percent within the upper limit and percent within the lower limit minus 100. Recommendations on tolerances on are shown in Table 2.8, based on the use of the standard deviation approach.

Table 2.8: Superpave LTMF tolerances based on standard deviation values (after *Cominsky, et al. 1998*)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.25	± 0.18	± 0.13	
Passing 4.75 mm and Larger sieves	± 3			± 3
Passing 2.36 mm to 150 µm sieves	± 2			± 2
Passing 75 µm sieve	± 0.7			± 0.7
Maximum Theoretical Specific Gravity	± 0.015			
Gyratory Compaction Property				
Air Voids	± 1			
Voids in Mineral Aggregate	± 1			
Voids Filled With Asphalt	± 5			
Bulk Specific Gravity	± 0.022			
Compaction Curve Slope	± 0.40			

As noted earlier, Cominsky et al., also discussed the use of the conformal index approach for use with Superpave mixes as an alternate to the use of standard deviation approach. Recommended tolerances when the conformal index approach is used are shown in Table 2.9.

Table 2.9: Superpave tolerances based on CI values (after *Cominsky, et al. 1998*)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.31	± 0.24	± 0.18	
Passing 4.75 mm and Larger sieves	± 4			± 4
Passing 2.36 mm to 150 µm sieves	± 3			± 3
Passing 75 µm sieve	± 0.8			± 0.9
Maximum Theoretical Specific Gravity	± 0.015			
Gyratory Compaction Property				
Air Voids	± 1			
Voids in Mineral Aggregate	± 1.5			
Voids Filled With Asphalt	± 5			
Bulk Specific Gravity	± 0.028			
Compaction Curve Slope	± 0.50			

Whether acceptance specifications are developed using the standard deviation or conformal index approach, very little information on the performance of Superpave mixes is yet available. This is true nationally and is especially true for Oregon. Certain states are more experienced with these mixes and will likely have performance information available soon. The applicability of this performance information to Oregon is not known.

2.3.2 Stone Matrix Asphalt Mixes

Recent work on specifications for stone matrix asphalt (SMA) mixes is included. An NCHRP report by Brown and Cooley provides guidelines for quality control/quality assurance procedures (*Brown and Cooley 1999*). Many of the recommended QC/QA procedures are not significantly different from procedures used with traditional dense-graded mixes. For example, the authors recommend that standard aggregate and binder testing procedures can be used, so long as provision is made for modified binders as appropriate. Sampling can also be accomplished using standard procedures, although it was noted that SMA mixes are stickier and low binder contents may be reported as a result.

The principal differences are the mixture testing area. Laboratory specimens are to be prepared using a 50-blow Marshall technique (*AASHTO T245*) or with 100 gyrations of the Superpave Gyratory Compactor (SGC). Only 70 gyrations are recommended for aggregates with L.A. Abrasion loss above 30 or when the design traffic levels are less than 1 million ESAL. Air voids in laboratory compacted mixtures should be in the 3-4 percent range. The authors recommend that although Method B of AASHTO T164 is very reliable, it is not suited to field work, due to the length of time needed for the test. They recommend that the asphalt content and gradation should be determined using the ignition furnace (*AASHTO TP53*). The tolerances shown in Table 2.8 are recommended. In-place density should be targeted to 95 percent of maximum theoretical specific gravity. The report also indicates that nuclear density gauges are not as accurate as when used with conventional dense-graded mixes, due to the rough surface texture of SMA mixers. Frequent calibration is therefore required.

Table 2.10: Gradation tolerance for extracted SMA samples

Sieve Size	Percent Passing Tolerance
19.0 mm	± 4.0
12.5 mm	± 4.0
9.5 mm	± 4.0
4.75 mm	± 3.0
2.36 mm	± 3.0
0.60 mm	± 3.0
0.30 mm	± 3.0
0.075 mm	± 2.0
Asphalt Content (%)	± 0.3

3.0 SPECIFICATION DEVELOPMENT

The development of an acceptance specification begins with the identification of measurable mix properties that relate to the desired performance. These properties may include characteristics of the mix itself (i.e., binder content) and properties of the mix after placement (i.e., in-place density). Results from the measurement of the selected mix properties should be available to the producer/contractor and agency in a timely manner, so that production processes can be modified if necessary.

1. Identification of Specification Parameters

Ideally the mix properties should be correlated with pavement performance through explicit relationships. Presently only a few pavement performance models with limited applicability are available. If explicit models are not available, then materials and pavement experts must identify implicit relationships or establish limits for the mix parameter. For example, it is well known that when mix with too much binder is placed, early permanent deformation (rutting) results. While there are laboratory tests that support this relationship, the relationships between field performance and laboratory measurements are not yet well established. Therefore experts must estimate the relationship or determine the reasonable limits for binder content that would minimize the likelihood of rutting.

2. Establish AQL & RQL

Once the models or limits are established, then the pavement experts must establish the acceptable and rejectable quality levels (AQL and RQL, respectively) for each parameter. These two levels were established because it is very difficult to establish a single level of quality that distinguishes between acceptable and rejectable work (*Phillips 1995*). Instead the AQL identifies the range of high quality work while the RQL identifies a minimum quality below which work is rejected. Between the two levels, work is considered to be poor enough to justify a pay reduction but not so poor as to warrant removal (*Weed 1994*). As discussed below, the FHWA and others have provided guidelines for the selection of AQL and RQL.

3. Establish α & β risks

There are risks associated with the acceptance or rejection of construction materials. These risks are inherent in the process, since the true value of a measured parameter cannot be known, only estimated, based on the limited sampling. Variability in the mix itself, sampling procedures, test equipment, and operators all contribute to the overall variability. The risks are of two types. The first type of risk is the contractor's risk, often termed α. This is the risk that the material produced or placed is truly of acceptable quality, but is rejected by the owner (agency). Clearly as this risk increases, the contractor compensates by increasing their bid price to recover the cost of removing acceptable material judged to be of inferior quality. The other risk, β, is the owner's risk that material which should have been rejected is accepted. When inferior quality materials are accepted, the performance of the pavement is adversely affected. The goal of the acceptance plan is to balance these two risks, though perfect balance is rarely achieved.

4. Sampling Plan

Once the AQL, RQL, α and β risks are established, the sampling plan can be developed that meets these criteria. In this context, the sampling plan refers to the number of samples that must be collected to meet the selected criteria (*AASHTO 1995*). AASHTO presents a process for the development of a statistically sound sampling plan. Often criteria require that the number of samples taken is greater than the number of samples historically collected. The cost of increased sampling must be weighed against the benefits of maintaining the desired levels of risk. When fewer samples are collected (or greater), then the α and β risks change even though the AQL and RQL remain constant.

5. OC Curves

The establishment of AQL, RQL, α and β also allow the operational characteristics (OC) curve to be developed. This well-established analytical procedure provides a graphical representation of the discriminating power of the acceptance procedure and ensures that the procedure is fair and effective. Details of OC curves are described below.

6. Pay Factors Established

Finally, the standard OC curve must be extended to include the expected pay factor. The revised OC curve graphically demonstrates the probable pay factor associated with each level of quality. Fairness dictates that when the contractor produces material at a quality level equal to that deemed acceptable by the agency (e.g., AQL), then they should on average receive the full bid price (e.g., pay factor = 1.00). The opportunity to earn at least some degree of bonus payment is necessary in order for a statistical acceptance procedure to pay an average of 100 percent when the work is exactly at the AQL (*Weed 1995*).

When multiple parameters are to be included in the specification, then the individual pay factors may be combined in some way to form a composite pay factor. Alternately, the minimum pay factor from among all pay factors may be used to compute contractor compensation (*Scholl 1991*). Several methods of combining pay factors to form a composite are used. Most agencies use some linear combination of pay factors with weighting factors applied to each component. The agency or a panel of pavement experts and contractors typically determines weighting factors.

In addition to the steps described above, the size of lot to be sampled, number of samples (sublots), location of sampling (means of locating sample within a sublot), size (quantity) of sample, appropriate test method, and action to be taken with result (non-compliance action, hold for total lot results, etc.) must be incorporated into the acceptance plan (*Puangchit, et al. 1982*). Each of these facets of the acceptance plan must be communicated to contractor and agency personnel.

3.1 ELEMENTS OF QUALITY ACCEPTANCE

A variety of parameters is used in HMA acceptance plans. As agencies move from prescriptive method specifications to performance-related specifications it appears that the number of parameters is reduced. In part, this trend is related to the goals of allowing the producer/contractor to innovate and control their process. As performance models that are more generally applicable become available, it may be that simple test(s) will allow the number of included parameters to be further reduced. This trend is shown schematically in Figure 3.1 and demonstrates that agency involvement would be reduced even further if warrants or design/build options were used.

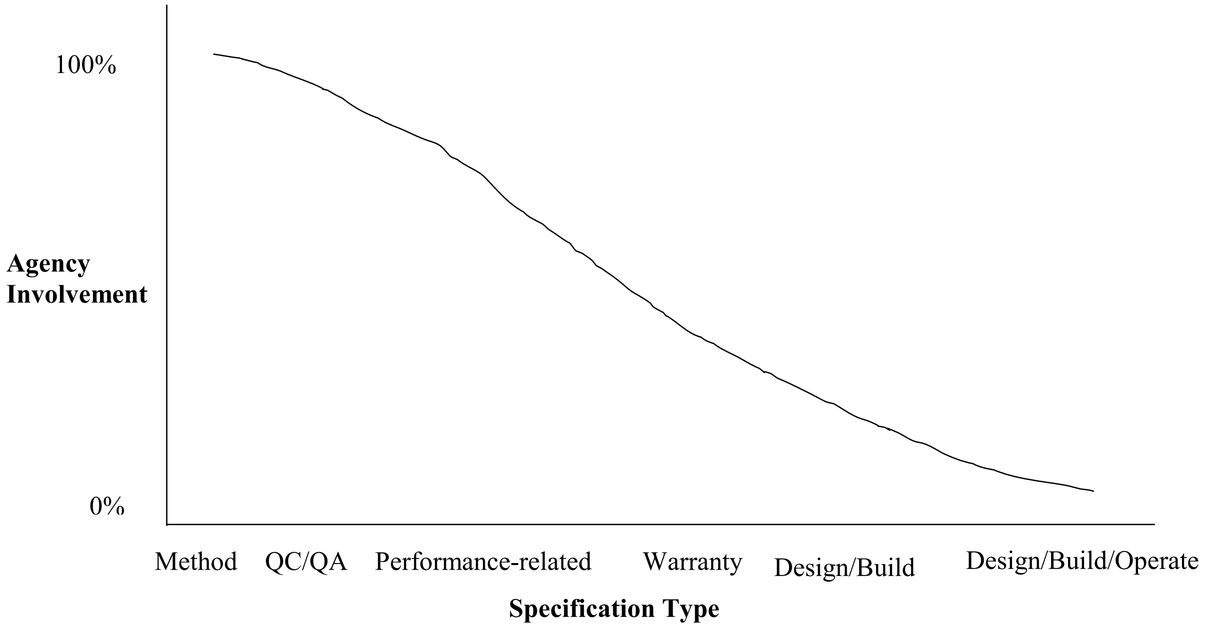

Figure 3.1: Agency involvement in HMA specifications (after *Schmitt, et al. 1998*)

The cost associated with acceptance testing is also of interest. Schmitt summarized information on the time required to complete various acceptance testing supplied by both agencies and contractors (*Schmitt et al. 1998*). These data are shown in Table 3.1. The data provide a practical means of establishing the frequency of testing based on contractor production.

Table 3.1: Minimum time requirements for HMA tests (after *Schmitt 1998*)

Test	Time, hours	Number of tests per 10-hour workday
Aggregate Gradation		
Coldfeed	1.75	5
Hot Bins	2.00	5
Plant Mixing		
Asphalt Content – Extraction	1.25	8
Asphalt Content – Ignition	1.00	10
Aggregate Gradation	2.50	4
Volumetrics	2.25	4
Density		
Cores	0.50	20
Nuclear Density Gauge	0.20	50

Acceptance plan parameters generally fall into one of two categories, production/mix property measurements or construction parameters. Each of these categories is discussed below.

3.1.1 Production/Mix Properties

The properties of the mix or mix constituents are measured either before or after mixing is completed. Often the mix is sampled and laboratory compacted specimens are prepared. The properties of the specimen are measured, and the values are compared to the job mix formula (JMF) values. As discussed below, sampling may be conducted on a quantity basis (i.e., once per 500 tons) or on a time basis (once every three hours). Quantity-based sampling has several advantages over time-based sampling. A given quantity of material can be tracked through plant mixing and laydown operations. Potential mix storage problems can be avoided and both small and large producers are tested at the same rate.

A paper by Schmitt, et al. (*1998*) surveyed state agencies and contractors to determine current practice with respect to acceptance testing. Some of the survey results are summarized below.

3.1.1.1 Gradation

Schmitt reported results on the role of gradation in acceptance testing for forty state agencies (*Schmitt et al. 1998*). The majority of agencies (30 of 40) use tonnage to define sublot and lot size, with sublot sizes ranging from 500 to 2000 tons. Some agencies use time to specify sublot and lot, for example one test for each three-hour increment. Other agencies only test aggregate gradation once for each mix design. Aggregates are sampled on the coldfeed or from the hot bins (17 of 41), from the truck (15 of 41) or from the mat (9 of 41). The most common measure of acceptance is quality level analysis similar to that currently used in Oregon.

The Oregon procedure currently includes up to nine aggregate sizes in their acceptance specification for dense-graded mix, depending on the maximum aggregate size. Schmitt reported that the most common aggregate sieve size used in pay adjustments is the 75 µm (25 of 40). The next most common sieve sizes are the 2.36 and 4.75 mm.

Although the majority of states report using weighted pay factors (25 of 38) to compute the composite pay factor, no consensus was found in the weighting factors assigned. Twelve states specify that the minimum individual pay factor be used in computing the composite pay factor (*Schmitt et al. 1998*). For example, if binder content and density are each PWL = 90 but the air voids are PWL = 80, then the PWL 80 would be used to compute the composite pay factor.

3.1.1.2 Mix Volumetrics

According to Schmitt, twenty-nine of forty-two state agencies specify mix volumetrics in their acceptance plans. Most agencies (15 of 29) sample the mix from truck while nine sample from the mat. Plant discharge is used by only four of the 29 agencies. Air voids is the most common mix volumetric reported, followed by voids in mineral aggregate. Only one state reports using void filled with asphalt, and one state includes the theoretical maximum specific gravity. As noted above, an increased use of mix volumetrics is expected as more states move to the Superpave system.

3.1.1.3 Performance Indicator Tests

Although some form of strength/performance tests is routinely conducted during the mix design phase, very few states currently use any “strength” tests as part of their acceptance plan. Schmitt reported that two of forty-two states use stability testing while the other agencies do not include any strength testing in their acceptance plan. Work is underway to develop a performance test suited to use in mix design and acceptance testing. The implementation date of the device is not known but is expected to be several years in the future.

3.1.2 Construction Elements

Many agencies include density, smoothness or both in their acceptance plans. Smoothness is particularly important because this parameter is most closely relative to the public’s perception of the quality of the project.

3.1.2.1 Density

Most state agencies measure field density based on sublots and lots described by tonnage, though a few states specify a lot based on area (*Schmitt 1998*). Approximately equal numbers of agencies use cores and nuclear density gauges. Most states follow the ASTM D2950-91 recommendation that at least seven cores/nuclear density measurements be used to establish the conversion factor. Most states reference the theoretical maximum specific gravity (TMD) while some state use the laboratory maximum specific gravity for their reference density. Schmitt reports that more states are planning to use TMD based on Superpave procedures.

3.1.2.2 Smoothness

Of the forty agencies responding, 26 reported including smoothness in their acceptance procedures. Fourteen did not include smoothness. The majority of the 26 agencies used

0.1 mile as the sublot size and the total project length as the lot size. Twelve of 26 agencies used the California Profilograph and judged acceptability based on the Profile Index (PI). No information was available on whether the PI was computed by hand or by means of computer evaluation. Blanking band vary from zero to 0.2 inch. Increasing use of profilers is reported (*NCHRP 1999*).

3.2 OPERATIONAL CHARACTERISTIC CURVES

Operational characteristic (OC) curves graphically represent the discriminating power of the acceptance procedure. They have been widely used in industrial applications for many years and are essential to the development of an equitable incentive/disincentive acceptance plan. A typical curve is shown in Figure 3.2.

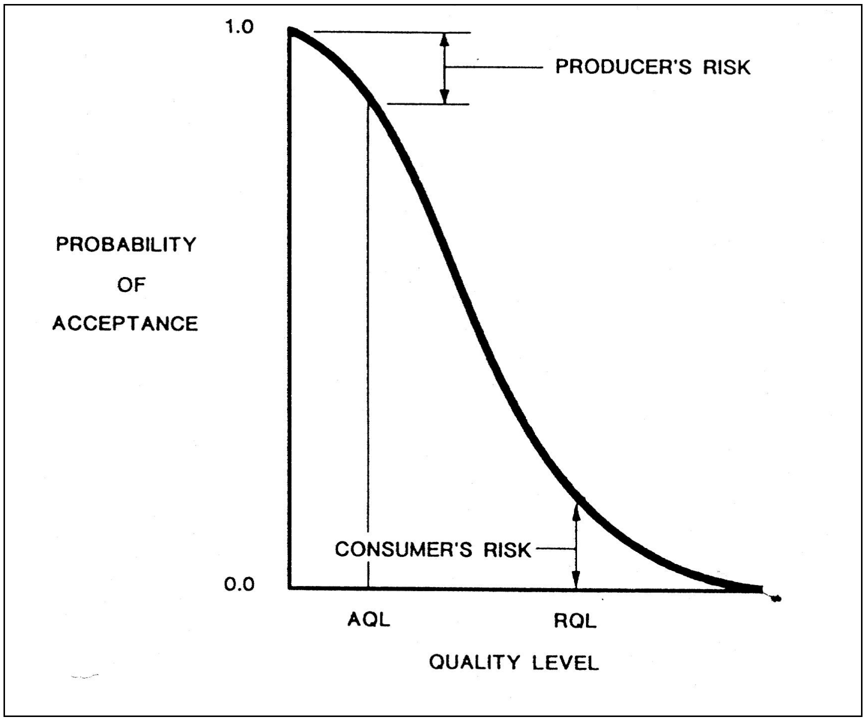

Figure 3.2: Conventional OC curve (after *Weed 1995*)

Four key elements of the OC curve and the acceptance plan are shown in Figure 3.2. These are the contractor and agency's risks (α and β risks) and the acceptable and rejectable quality levels (AQL and RQL). Each of these factors must be selected before the OC curve can be developed. The construction of OC curves is fairly straightforward once the risk and quality levels are set. The procedure is described in AASHTO Recommended Practice R 9-90. (*AASHTO 1995*). In addition, computer programs (i.e., OCPLOT) are available that allow rapid construction of the curves. (*Weed 1995*).

Recommended risk levels are provided in the AASHTO Recommended Practice based on the criticality of the parameter, where criticality is used to express the relative importance of the various factors. Probability values are shown in Table 3.2 for each of the four levels of criticality.

Table 3.2: Guidelines for α and β risks

Classification	Probability of Acceptance at RQL (buyer's risk)	Probability of Acceptance at AQL	Seller's Risk at AQL
Critical	0.005	0.950	0.050
Major	0.050	0.990	0.010
Minor	0.100	0.995	0.005
Contractual	0.200	0.999	0.001

Another form of OC curve is shown in Figure 3.3. Here the probability of acceptance is replaced with the expected pay factor. In the example shown, material produced at the AQL would receive, on average, a pay factor of 100 while truly superior work would receive a bonus of up to 102. RQL work would receive a pay factor of 70. The opportunity to earn a bonus is necessary in order for a statistical acceptance procedure to pay an average of 100 percent when the work is at the AQL. Unless bonuses and reductions are allowed to balance out, the average pay factor will be biased downward. Contractors producing material at an acceptable quality level would not receive 100 percent pay on average, unfairly penalizing them for work that is of acceptable quality (*Weed 1995*).

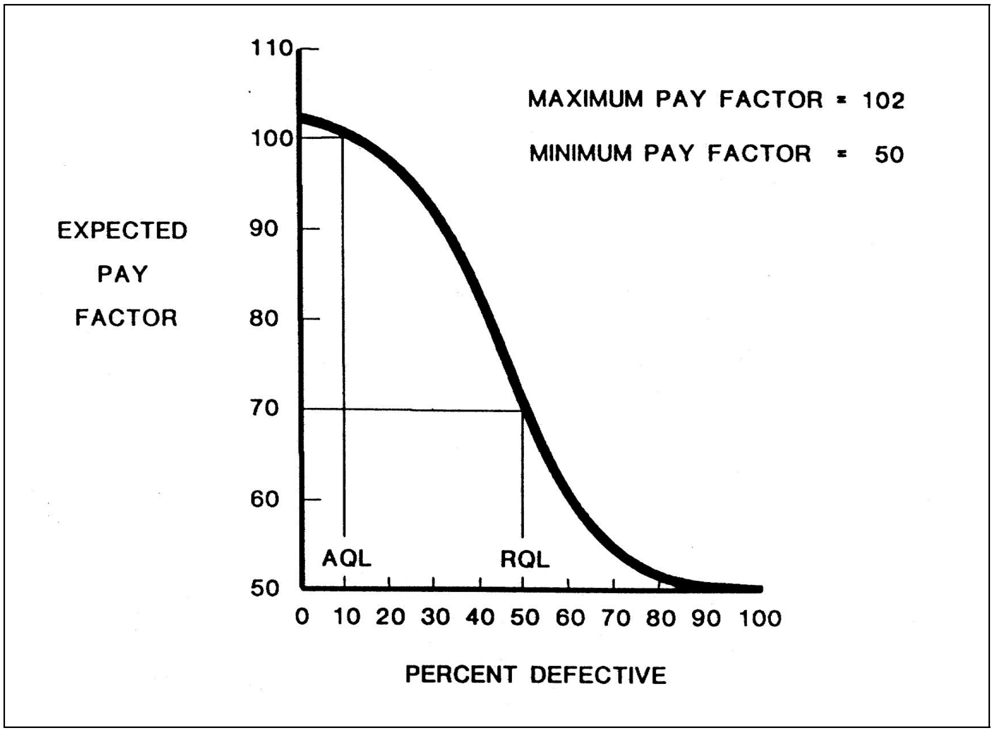

Figure 3.3: Typical OC curve for statistical acceptance procedure with adjusted pay schedule (after *Weed 1995*)

The development of OC curves is based on first determining the percent defective in each lot using a beta distribution function and coupling the percent defective to the noncentral *t* distribution. The noncentral *t* distribution allows the probability of acceptance to be determined for each level of population percent defective. The OC curve results from plotting the probability of acceptance against the percent defective. Additional details on the theory of the beta and noncentral *t* distributions are described in the AASHTO manual (*AASHTO 1995*).

3.2.1 Construction Variability

Variability in construction and material production is inevitable. The magnitude of the variability plays an important role in both the development of the construction specification and in its implementation. Consider the following example.

Assume that the JMF binder content is 5.5 percent and that pavement experts have determined that binder contents that vary more than ± 0.5 percent from the JMF value result in poor performance (either raveling or flushing). Further assume that a typical standard deviation for binder content is 0.25 percent. If the AQL is 10 percent, then Figure 3.4 illustrates a process that could be used to set the tolerance for binder content.

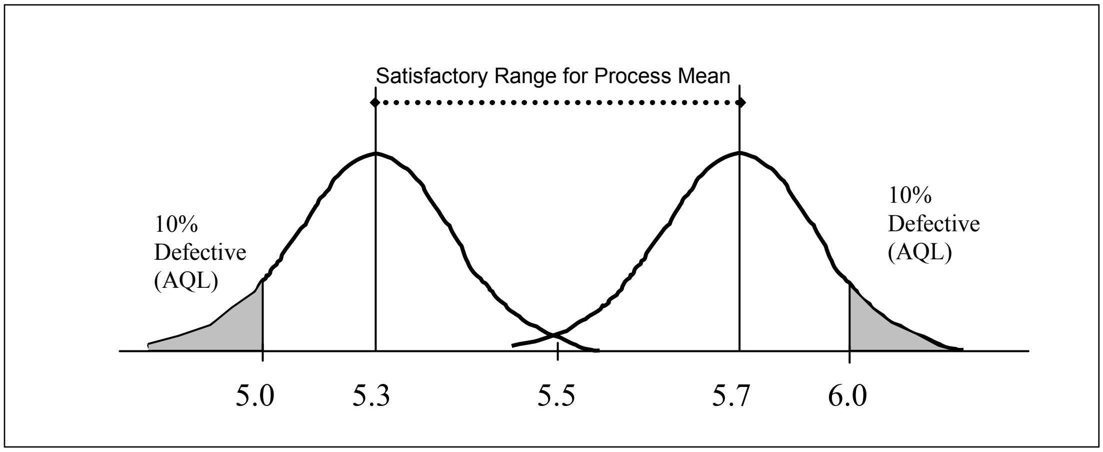

Figure 3.4: Illustration of latitude permitted in setting process mean

This example demonstrates the importance of the standard deviation in setting the tolerance for any of the specification parameters.

Construction variability was summarized in a recent NCHRP Synthesis (*Hughes 1996*). Only the information on hot mix asphalt is included here. The standard deviation of asphalt content was founded to vary from 0.15 to 0.44 percent (see Table 3.3). The variability was found to be different for different test procedures. Only limited information was available for ignition testing. No information on the number of projects or data points was reported.

Table 3.3: Typical asphalt content variability (*Hughes 1996*)

Source	Year	Test	Std. Dev., %
Arkansas	1994	Extraction	0.21
Virginia	1994	Extraction	0.18
Virginia	1994	Nuclear	0.21
NCAT	1994	Nuclear	0.19
NCAT	1994	Centrifuge	0.44
NCAT	1994	Ignition	0.30
Washington	1993	Extraction	0.24
Colorado	1993	Extraction	0.15
Kansas	1988	Nuclear	0.27
Virginia	1988	Extraction	0.19
Pennsylvania	1980	Extraction	0.25
BPR	1969	Extraction	0.28
Virginia	1968	Extraction	0.25

All these data are for virgin mixes, e.g., without recycled asphalt pavement (RAP). Two agencies (Louisiana and Indiana) studied the effects of RAP on the standard deviation of asphalt content. Standard deviations for mixes containing 20 to 30 percent RAP were not significantly different from those for mixes containing no RAP.

It was also reported that two studies compared DOT and contractor results. Alabama DOT reported a DOT standard deviation of 0.239 compared to 0.170 for contractor tests when both used the nuclear test. Virginia reported 0.21 and 0.18 for extraction and nuclear testing, respectively, while contractor test results were 0.16 and 0.13 for extraction and nuclear tests. It was noted that these results were taken from limited studies.

Hughes also presented the standard deviations for volumetric properties of laboratory compacted specimens. Data on air voids, VMA and voids filled with asphalt were included for several different compaction techniques. The results are shown in Table 3.4. It is interesting to note that the average results for the SHRP gyratory and Marshall compaction techniques are very similar though the SHRP gyratory is slightly lower.

Table 3.4: Standard deviations of volumetric properties from laboratory compacted mixtures

Source	Year	Compactor	Air Voids, %	VMA, %	VFA, %
NCHRP	1995	SHRP Gyratory	0.70	0.90	4.24
FHWA	1994	SHRP Gyratory	0.5	0.4	-
Virginia	1994	Marshall	0.86	0.7	3.5
Colorado	1993	Texas Gyratory	0.3	0.3	2.7
Colorado	1993	Linear Kneading	1.3	-	-
Colorado	1993	French Plate, 100 mm	1.4	-	-
Colorado	1993	French Plate, 50 mm	0.7	-	-
FHWA	1991	Marshall	0.7	0.6	-
West Virginia	1989	Marshall	0.5	-	-
Virginia	1989	Marshall	0.9	0.9	4.1

Variability of air voids in field compacted mixes is also reported by Hughes. Table 3.5 shows data from six agencies. The standard deviations of the field compacted mixes are 2 to 3 times that reported for laboratory compacted specimens. Hughes notes that this difference must be reflected when specifying field air voids, and he recommends specification limits of 3 to 8 percent. The same limits could be applied to field density (percent compaction).

Table 3.5: Standard deviations of air voids for roadway compacted mixtures (*Hughes 1996*)

Source	Year	Method	Air Voids, %
California	1995	Cores	1.9
New Jersey	1995	Cores	1.5
Ontario	1995	Cores	1.6
Colorado	1993	Cores	1.0
Washington	1993	Nuclear	0.9
Virginia	1984	Cores	1.3

Hughes also reported variability in pavement smoothness. Only limited data was available, in part, because smoothness is often reported as a single value for a project, rather than multiple measurements taken over the length a project. The standard deviations of computerized profilographs are available and range from 0.008 to 0.016 m/km (0.5 to 1.0 in/mile). Hughes also reported on a study conducted by the FHWA Western Federal Lands Highway Division in 1994. A California-type profilograph was used to determine the profile indices for new construction dense-graded mixes and multi-lift dense-graded overlay projects. The pooled standard deviations were 0.030 m/km (1.9 in/mi) and 0.035 m/km (2.2 in/mi) for the new construction and overlay projects, respectively.

Data was also available from Oregon DOT projects (*Remily 2000*). These data are summarized in Table 3.6.

Table 3.6: ODOT variability data

CONSTITUENT	No. of Data Points (projects)	Ave COV	Ave St Dev	No. of Sublots in project	
				Min.	Max.
Pb, % (Incinerator)	81	3.04	0.17	3	89
Pb, % (Meter Method)	60	1.20	0.07	3	40
Air Voids, %	18	15.4	0.6	5	89
VMA, %	18	3.9	0.6	5	89
Compaction, %	116	0.6	0.6	3	89

These data were collected from a variety of large and small projects constructed by several different contractors. Mix property data were taken from specimens prepared using gyratory compaction equipment. The variability on ODOT projects is generally lower than that reported by Hughes.

3.2.2 Simulation Procedures

The uses of operational curves are essential to the successful development of specifications. Additional information on the performance of a proposed specification, however, can be gained through simulation. Questions that can be answered using simulation techniques that cannot be answered with OC curves alone include:

- Sensitivity of risks (contractor and agency) to specific levels of variability in the measurement device; and
- Production variability, i.e., density variability across or along the mat.

Simulation analysis also allows examination of the tradeoff between number of samples and risk.

The development of simulation software is beyond the scope of this project; however, Illinois DOT recently contracted with the University of Illinois to prepare such software. The result of this effort, ILLISIM, is available from the University of Illinois.

4.0 QUALTIY ASSESMENT AND CONTRACTOR PAYOUT FOR DENSE-GRADED MIXES

The quality characteristics, their relative importance, and the target values to be used in assessing the quality of dense-graded mixes were determined. It was then decided that two product characteristics summarized the overall mix quality. The two product characteristics or factors are 1) in- place density measured as a percent and 2) percent air voids in the mix. The factors, their relative importance weights, and target values are given in Table 4.1. The target for density depends on the sieve size, and the sum of the relative importance weights must equal 100%.

Table 4.1: Factors, relative importance, and targets

Factor	Relative Importance, w	Target Value, T
Density (9.5 mm & 12.5mm mixes	50%	92.5%
Density (19 mm mixes)	50%	93.5%
Air Voids	50%	4% or Determined from project JMF

For each factor, two measures of quality are considered: 1) closeness of the factor to its specified target, and 2) the variability of the factor. The goal for dense-graded mixes is for the factors to be consistently close to their targets. To do this, factor measurements taken during production, or in the field, should have small differences between the measurement and the target. The variability in the measurements should also be small.

Contractors are employed for a large portion of the asphalt paving jobs in Oregon. The bid price of a job is established prior to commencing a job. Upon completion, the quality of the pavement is assessed and if it is determined to exceed expectations, a pay bonus is given to the contractor. If the quality of the pavement is below expectations, a pay penalty is imposed. The bonus, or penalty, is determined from a pay factor. The pay factor is a number between 0.75 and 1.05 that is multiplied by the original contract price to determine the end payout. The pay factor is a function of the measures of quality for the factors; i.e., it depends on 1) closeness to target and, 2) variability of the factors.

4.1 COMPUTING THE STATISTICAL QUALITY MEASURES

This section discusses the formulation and calculations for computing the two statistical quality measures. The complete model and corresponding notation is defined in Appendix A.

4.1.1 Measurements

During the production of a mix lot, tests are conducted on the factors, and the measurements are recorded. Let a factor measurement be represented by *X* and the corresponding target represented by *T*. Table 4.2 shows some sample measurements for air voids and density along with sample targets. Notice that the number of measurements for each factor need not be equal.

Table 4.2: Sample data and computations of quality measures

Row	**Measurement X**		**Target T**	
	Air Voids (%)	Density (%)	Air Voids (%)	Density (%)
1	3.9	91.0	4.0	93.5
2	3.6	92.2	4.0	93.5
3	3.4	91.6	4.0	93.5
4	3.3	92.1	4.0	93.5
5	3.2	92.9	4.0	93.5
6		92.6		93.5
7		93.1		93.5
Average Measurement $\overline{X}$	3.48	92.21		
Closeness to Target Δ	0.27	1.65		
Variability S^2	0.08	0.54		

4.1.2 Computing Closeness to Target

To quantify the closeness of a factor to its target, the squared difference between the average measurement and the target is computed. This quantity is represented as Δ and is computed as:

$$\Delta = \left(\overline{X} - T\right)^2 \qquad \textbf{(4-1)}$$

where, $\overline{X}$ is the average value of the measurements for a factor. For example, in Table 4.2 the average value of the five measurements for air voids is $\overline{X} = 3.48$ and the corresponding target is *T=4*, therefore Δ is computed as $\Delta = (3.48 - 4)^2 = 0.27$.

4.1.3 Computing Variability

To quantify the variability of a factor, the sample variance of the measurements is computed. This quantity is represented by S^2 and is computed as:

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \overline{X}\right) \qquad \textbf{(4-2)}$$

where, n is the total number of measurements for the factor. Using the data in Table 4.2 we see that the number of measurements for air voids is $n = 5$ and the sample variance is calculated as

$$S^2 = \left[\begin{array}{l} (3.9-3.48)^2 + (3.6-3.48)^2 + (3.4-3.48)^2 \\ +(3.3-3.48)^2 + (3.2-3.48)^2 \end{array} \right] \Big/ (4) = 0.08 .$$

4.1.4 Changing Factor Targets

It may be necessary during the production of a mix lot to make adjustments to the process. Adjustments are usually done in the early stages of production while the placement process is being fine-tuned, or are made due to changes in aggregate properties. The adjustment often results in a change in the target value. For a given mix lot, one might have target level changes for one or more of the factors. If target levels change, Δ and S^2 are computed separately for each target change and weighted averages of Δ and S^2 are used as the quality measures.

The calculations are best explained with an example. Consider the sample data in Table 4.3. For measurements 1 thru 5, the target value for air voids is 4.0 and for measurements 6 thru 9, the target value changes to 4.3. Δ and S^2 are computed separately for each set of measurements, so for target 1, $\Delta_1 = 0.27$ and $S_1^2 = 0.08$ and for target 2, $\Delta_2 = 1.27$ and $S_2^2 = 0.14$. A weighted average is computed for Δ and S^2 where the weights are the number of measurements for each target. Specifically, the weighted average for Δ is computed as,

$$\overline{\Delta} = \frac{1}{n} \sum_{j=1}^{jMax} t_j \Delta_j \qquad \textbf{(4-3)}$$

and the weighted average for S^2 is computed as,

$$\overline{S^2} = \frac{1}{n} \sum_{j=1}^{jMax} t_j S_j^2 \qquad \textbf{(4-4)}$$

where, n is the total number of measurements for a factor, j is the index for each different target, $jMax$ is the total number of target changes, and t_j is the number of measurements corresponding to the j^{th} target. For the air void data shown in Table 4.3, $n = 9$, $t_1 = 5$, $t_2 = 4$.

The weighted average for Δ is computed as $\overline{\Delta} = \frac{1}{9}\left[(5)(0.27) + (4)(1.27)\right] = 0.71$ and the weighted average for S^2 is computed as $\overline{S^2} = \frac{1}{9}\left[(5)(0.08) + (4)(0.14)\right] = 0.11$.

Table 4.3: Sample data and calculations of quality measures for changing target values

Row	Measurement X		Target T	
	Air Voids (%)	Density (%)	Air Voids (%)	Density (%)
1	3.9	91.0	4.0	93.5
2	3.6	92.2	4.0	93.5
3	3.4	91.6	4.0	93.5
4	3.3	92.1	4.0	93.5
5	3.2	92.9	4.0	93.5
6	5.5	92.6	4.3	93.5
7	4.9	93.1	4.3	93.5
8	5.5		4.3	
9	5.8		4.3	

	Target 1	
Δ_1	0.27	1.65
S_1^2	0.08	0.54
	Target 2	
Δ_2	1.27	
S_2^2	0.14	
	Weighted Averages	
$\overline{\Delta}$	0.71	1.65
$\overline{S^2}$	0.11	0.54

4.1.5 Mapping Quality Measures to a Pay Factor

For each factor, the quality measures $\overline{\Delta}$ and $\overline{S^2}$ are converted to an individual pay factor by a function that maps an equitable pay factor to the expected value of a quality measure. The quality measures $\overline{\Delta}$ and $\overline{S^2}$ are in squared units, but it is more intuitive to work in terms of straight units when mapping to a pay factor. Straight units are obtained by taking the square root of the quality measures, i.e., $\sqrt{\overline{\Delta}}$ and $\overline{S}$. Preliminary expected values for $\sqrt{\overline{\Delta}}$ and $\overline{S}$ were established by the research team and are shown in Table 4.4. These values represent a reasonable starting point but may be changed after some actual project experience. For example, if $\sqrt{\overline{\Delta}} = 0.7$ for air voids, a pay factor of 1.00 would be assigned.

Table 4.4: Preliminary mappings between the expected quality measure and pay factor

Pay Factor	Air Voids (%)		Density (%)	
	Closeness to Target $\sqrt{\overline{\Delta}}$	Variability $\overline{S}$	Closeness to Target $\sqrt{\overline{\Delta}}$	Variability $\overline{S}$
1.05	0.2	0.3	0.3	0.3
1.00	0.7	1.0	0.9	0.9
0.75	1.5	1.2	1.5	1.5

In practice, values for $\sqrt{\overline{\Delta}}$ and $\overline{S}$ will not be exactly equal to the values given in Table 4.4. Therefore, a piecewise continuous function to map $\sqrt{\overline{\Delta}}$ and $\overline{S}$ to pay factor values is determined by linear interpolation. To illustrate, consider the quality measure for closeness to target $\sqrt{\overline{\Delta}}$ for air voids. A graph of the function that maps $\sqrt{\overline{\Delta}}$ for air voids to a pay factor is shown in Figure 4.1 and the equation of the function is shown in Equation 4-5.

$$PF_{\left(\sqrt{\overline{\Delta}},\ Percent\ Air\,Voids\right)} = \begin{cases} 1.05 & \sqrt{\overline{\Delta}} \le 0.2 \\ -0.10\left(\sqrt{\overline{\Delta}}\right)+1.07 & 0.2 < \sqrt{\overline{\Delta}} \le 0.7 \\ -0.31\left(\sqrt{\overline{\Delta}}\right)+1.22 & 0.7 < \sqrt{\overline{\Delta}} \le 1.5 \\ 0.75 & \sqrt{\overline{\Delta}} > 1.5 \end{cases} \qquad \textbf{(4-5)}$$

Similarly, the functions for $\overline{S}$ for air voids and for $\sqrt{\overline{\Delta}}$ and $\overline{S}$ for density are determined from the mappings in Table 4.4.

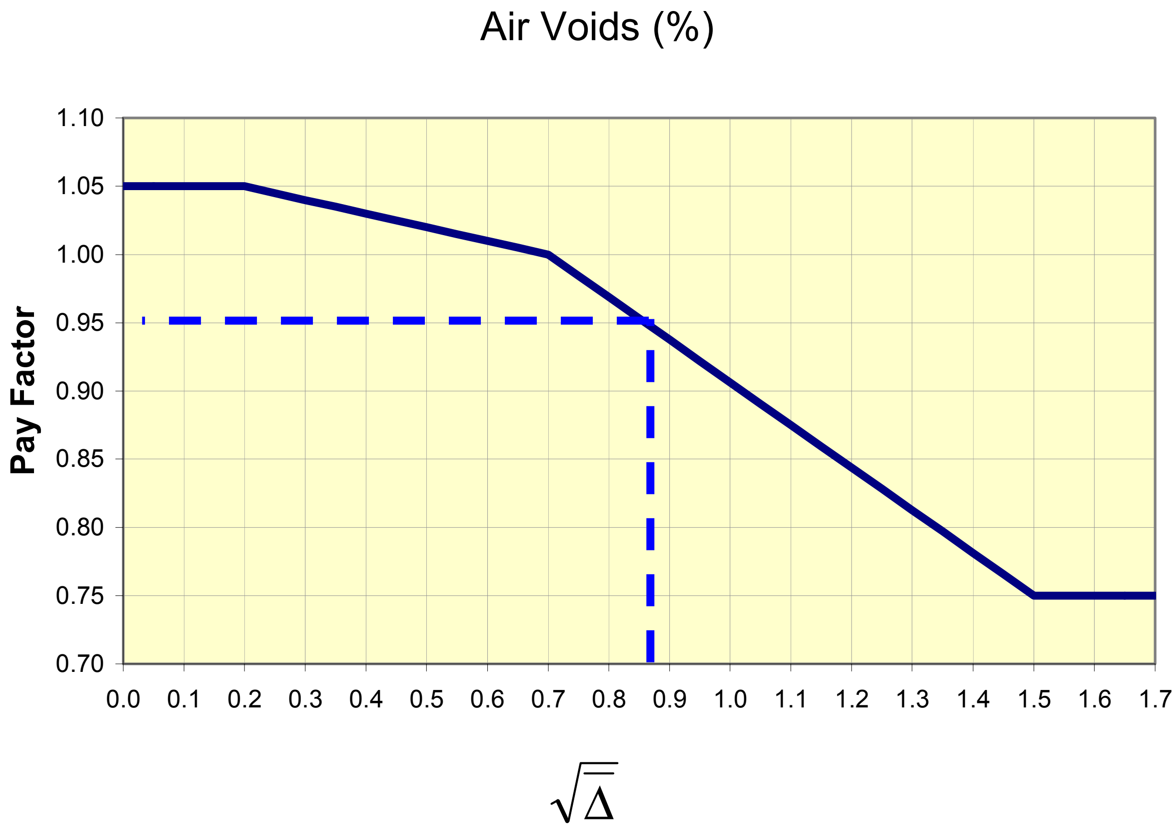

Figure 4.1: Graph of function to map closeness to target for air voids to pay factor

For example, the quality measure for closeness to target for air voids in Table 4.3 is mapped to a pay factor by substituting $\sqrt{\bar{\Delta}} = \sqrt{0.71} = 0.84$ into Equation 4-5 to get $PF_{\left(\sqrt{\bar{\Delta}},\ Percent\ Air\, Voids\right)} = -0.31\left(0.84\right) + 1.22 = 0.95$. The dashed line in Figure 4.1 shows the mapping graphically. From the data in Table 4.3, the pay factors are computed and are listed in Table 4.5.

Table 4.5: Individual and composite pay factors for sample data

Air Voids (%)		Density (%)		
Quality Measure	**Pay Factor**	**Quality Measure**	**Pay Factor**	
$\sqrt{\bar{\Delta}} = \sqrt{0.71} = 0.84$	0.95	$\sqrt{\bar{\Delta}} = \sqrt{1.65} = 1.29$	0.84	**0.90**
$\sqrt{\overline{S^2}} = \sqrt{0.11} = 0.33$	1.05	$\sqrt{\overline{S^2}} = \sqrt{0.54} = 0.74$	1.01	**1.03**
	1.00		**0.93**	**0.96**

░ Intermediate Values
▓ Composite Pay Factor

4.1.6 Computing Intermediate Values and Composite Pay Factors

An "intermediate pay factor" is computed to convey information about how a particular factor is performing relative to another factor, or how $\sqrt{\overline{\Delta}}$ is performing relative to $\overline{S}$. The intermediate values, denoted V, are computed as weighted averages using the relative importance weights in Table 4.1. For example, from Table 4.1 and Table 4.5, the intermediate value for air voids is $V_{Air\,Voids} = w_{Air\,Voids}\left(0.95+1.05\right) = \left(0.5\right)\left(0.95+1.05\right) = 1.00$ and the intermediate value for closeness to target is
$V_{\sqrt{\overline{\Delta}}} = w_{Air\,Voids}\left(0.95\right) + w_{Density}\left(0.84\right) = \left(0.50\right)\left(0.95\right) + \left(0.50\right)\left(0.84\right) = 0.90$.

All four intermediate values are shown in Table 4.5 in the light gray cells. It is important to note when interpreting the intermediate values that although they are weighted averages of the individual pay factors, they should not be viewed as pay factors, but as measures of relative performance.

The composite pay factor for the entire lot is the simple average of the intermediate values as,

$$PF = \frac{1}{f}\left(V_{Air\,Voids} + V_{Density}\right) \qquad \textbf{(4-6)}$$

where, f is the total number of factors. For the sample data, the composite pay factor is, $PF = \frac{1}{2}\left(1.00+0.93\right)$. The composite pay factor is shown in dark gray in Table 4.5.

4.2 CONFIGURABILITY OF THE QUALITY ASSESMENT METHOD

The statistical quality assessment methodology developed here is flexible and allows ODOT the ability to change several features such as the type and number of factors, the relative importance of the factors and the values used to map the quality measures to pay factor values.

5.0 SMOOTHNESS MEASUREMENTS

As part of the work associated with the development of dense-graded acceptance procedures, the research evaluated smoothness data from a number of ODOT projects. Data were collected using ODOT's Profilometer (ultrasonic) and, for some projects, contractor-owned lightweight profilers (laser). The purpose of the evaluation was to provide input on possible changes to existing specifications.

This chapter describes the statistical analyses of the available data and presents conclusions based on the analyses. The goal is to provide statistically sound analyses for ODOT personnel as they make decisions regarding the implementation of an alternate smoothness specification for asphalt paving.

5.1 DESCRIPTION OF DATA

The data were collected in two distinct sets. Data Set A consists of project identification information (contract no., location, project type, etc) and International Roughness Index (IRI) values for before and after the rehabilitation project was completed. Complete records are not available for all of the 445 projects in Set A.

Data Set B contains both ultrasonic- and laser-based IRI values for the same sections of 51 projects constructed in 1999 and 2000. These data are shown in Appendix B.

For purposes of comparison, the different mix types identified in Sections 5.1.1 and 5.1.2 are described in their respective Superpave designations and shown in Table 5.1.

Table 5.1: Superpave mix types

Mix Type	Superpave Designation
C	12.5 mm Dense Graded
B	19 mm Dense Graded
F	19 mm Open Graded

5.1.1 Data Set A

Data set A contains IRI measurements collected on a wide variety of projects. Projects that were not related to hot-mix asphalt surface courses were eliminated. Projects with E-mix or stone matrix asphalt (SMA) surfaces were also excluded since there were too few projects available for analysis. The emulsion asphalt concrete (EAC) projects were excluded because the research focused on hot mix asphalt. After eliminating these records, 343 of the original 445 projects remained. Note that the data is presented "as provided", except that the project length was coded to the following: short (0 to 2 miles), medium (2.1 to 6 miles) and long (greater than 6 miles).

5.1.2 Data Set B

Data set B contains both ultrasonic and laser devices which were used on a total of 47 projects. All ultrasonic measurements were made using the ODOT-owned Profilometer. Light-weight, laser profiling was completed using five different contractor-owned profilers. Ultrasonic measurements were taken 1 to 8 weeks after the laser measurements were completed. The surface course of most projects (37 of 47) was an open-graded mix (F-mix). A summary of the data in Data Set B is shown in Table 5.2.

Table 5.2: Data Set B - project information

Wearing Course Type	Number of Projects	Number of Different Profilers Used	Laser Profiler		Ultrasonic Profilometer	
			Averarge IRI	Average Standard Deviation	Average IRI	Average Standard Deviation
B	8	2	1013	208	1293	288
F	37	4	1034	135	1251	150
SMA	2	1	838	111	1247	162

5.2 DATA ANALYSIS

5.2.1 Laser Profiler vs. Ultrasonic Profilometer

The goal of the data analysis was to determine whether a relationship could be established relating the IRI values, computed from measurements taken by the laser profiler, to measurements taken with the ultrasonic profilometer.

Summary statistics for both sets of IRI measurements are shown in Table 5.3. Since the standard skewness and standard kurtosis results for both data sets fall between -2 and +2, the assumption of normality is valid for both the means and standard deviations of both data sets.

Table 5.3: Summary statistics for laser and ultrasonic IRI values

Summary Statistics for Laser IRI		Summary Statistics for Ultrasonic IRI	
Count =	47	Count =	47
Average =	1021.64	Average =	1258.13
Variance =	14403.8	Variance =	11641.9
Standard Deviation =	120.016	Standard Deviation =	107.897
Minimum =	758.0	Minimum =	1040.0
Maximum =	1333.0	Maximum =	1495.0
Range =	575.0	Range =	455.0
Stnd. skewness =	0.529791	Stnd. skewness =	1.5071
Stnd. kurtosis =	0.165998	Stnd. kurtosis =	-0.101053

If it is assumed that all of the profilers were identical (which is a poor assumption), then the IRI measurements could be considered “paired samples”. The associated analysis looks at the difference between each pair of measurements (ultrasonic minus laser) to determine if there is a statistically significant difference.

In this case, there is a statistically significant difference between the two measurement techniques. This is true when all surface types are considered together and when only the F-mix projects are considered. On average, the ultrasonic IRI measurements are about 230 units higher than the laser IRI measurements, as shown in Figure 5.1.

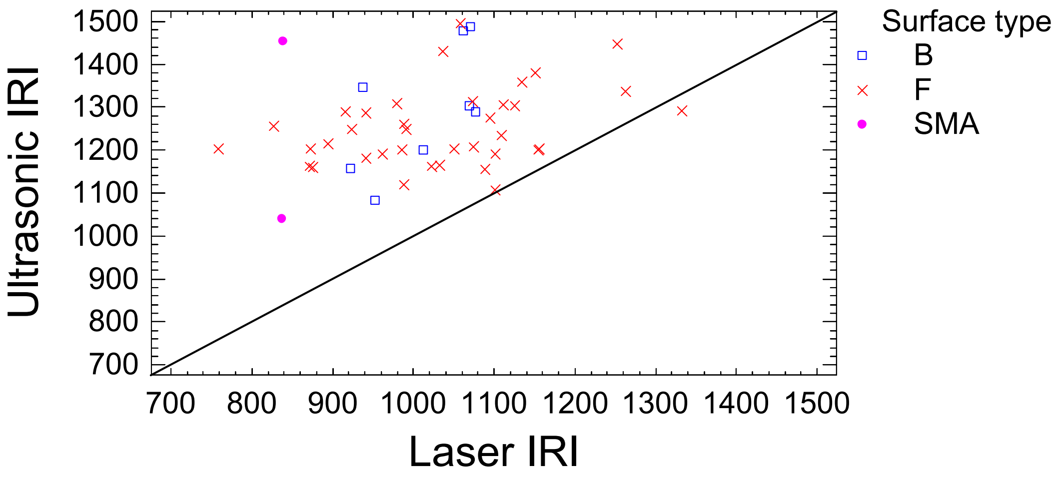

Figure 5.1: Comparison of laser and ultrasonic IRI by surface type

There was some concern that the ultrasonic measuring device (profilometer) would yield consistently higher IRI values for the F-mix projects due to the "noise" produced by the open texture of the mix. This concern cannot be thoroughly addressed given the available data considering that four different profilers were used in the investigation. However, one profiler was used to collect the majority of the data (27 of 47 projects).

These data were used to examine the possibility that F-mix IRI values were significantly different from B-mix values by treating the data as paired samples. The results are shown in Table 5.4. The data set is relatively small, but based on these data there is no statistical difference between the results for F- and B-mix projects.

Table 5.4: Comparison of laser- and profilometer-based IRI values

Project Type	Number of Projects	Average Difference of Paired Measurements, Laser – Profilometer IRI, mm/km
B-mix	6	-172
F-mix	21	-170

5.2.2 Summary of Analysis

The overall goal of the analysis was to establish a useful relationship between ultrasonic and laser IRI measurements. A General Linear Model (GLM) approach was used to attempt to establish the relationship. Predictors included: the surface type (3 types), profiler (4 profilers) and the ultrasonic measurement. The limited data set precluded including two-way interactions in the model. The analysis results are shown in Tables 5.5 and 5.6. The analysis indicates that:

- There are statistically significant differences between profilers. This is not surprising since no effort was made to calibrate the profilers to a single standard prior to use. Furthermore, since two-way interactions could not be included in the analysis, some or all of the reported differences may be due to the different surface types.
- Table 5.6 shows that SMA surfaces are statistically different (less roughness) from both the F and B mixes. However, it should be noted that only two SMA projects were included in the available data.

Table 5.5: Multiple comparisons for laser by profiler - method: 95.0 percent LSD

Profiler	Count	LS Mean	LS Sigma	Homogeneous Groups
LTM1	4	774.1	48.8	X
MBI1	10	860.1	34.3	XX
BY1	4	914.8	48.8	XX
JCC1	29	990.6	23.4	X

Contrast	Difference	+/- Limits
BY1-LTM1	*140.7	120.2
BY1-MBI1	54.6	101.5
JCC1-LTM1	*216.5	92.6
JCC1-MBI1	*130.4	63.1
LTM1-MBI1	-86.0	101.5

* Denotes a statistically significant difference

Table 5.6: Multiple comparisons for laser by surface type - method: 95.0 percent LSD

Surface Type	Count	LS Mean	LS Sigma	Homogeneous Groups
SMA	2	735.6	63.1	X
B	8	929.5	34.5	X
F	37	989.6	17.3	X

Contrast	Difference	+/- Limits
B – F	-60.1	68.4
B – SMA	*193.9	135.9
F – SMA	*254.0	125.6

* Denotes a statistically significant difference.

Table 5.7 summarizes the results of fitting a general linear statistical model relating the Laser to three predictive factors. Since the P-value in the first ANOVA table for Laser is less than 0.01, there is a statistically significant relationship between Laser and the predictor variables at the 99% confidence level.

Table 5.7: Type III sums of squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Profiler	237468.0	3	79156.0	11.19	0.0000
Surface type	130496.0	2	65248.2	9.22	0.0005
Ultrasonic	45152.1	1	45152.1	6.38	0.0156
Residual	283036.0	40	7075.9		
Total (corrected)	**662573.0**	**46**			

R-Squared = 57.3 percent
R-Squared (adjusted for d.f.) = 50.9 percent
Standard Error of Estimate = 84.1
Mean absolute error = 62.2

The ANOVA table for Laser tests the statistical significance of each of the factors as it was entered into the model. Notice that the highest P-value is 0.0156, belonging to the Ultrasonic device. Since the P-value is less than 0.05, that term is statistically significant at the 95% confidence level.

The R-Squared statistic indicates that the model, as fitted, explains 57.3% of the variability in Laser. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 50.9%. The standard error of the estimate shows the standard deviation of the residuals to be 84.1.

The form of the model is shown in Equation 5.1 and the 95.0 percent confidence intervals for the coefficients are shown in Table 5.8.

Table 5.8: 95.0 percent confidence intervals

Parameter	Estimate	Standard Error	Lower Limit	Upper Limit
CONSTANT	512.995	148.703	212.455	813.535
Profiler	29.8826	34.3686	-39.579	99.3443
Profiler	105.693	20.8295	63.5949	147.791
Profiler	-110.817	34.3448	-180.231	-41.4035
Surface type	44.5837	28.8135	-13.6507	102.818
Surface type	104.723	24.7039	54.7941	154.651
Ultrasonic	0.295604	0.117021	0.0590962	0.532112

The equation of the fitted model is:

$$Laser = 512.995 + \begin{bmatrix} (29.8826 * I1(1)) + (105.693 * I1(2)) - \\ (110.817 * I1(3)) + (44.5837 * I2(1)) + \\ (104.723 * I2(2)) + (0.295604 + ultrasonic) \end{bmatrix} \quad \textbf{(5-1)}$$

where,

I1(1) = 1 if Profiler=BY1, -1 if Profiler=MBI1, 0 otherwise
I1(2) = 1 if Profiler=JCC1, -1 if Profiler=MBI1, 0 otherwise
I1(3) = 1 if Profiler=LTM1, -1 if Profiler=MBI1, 0 otherwise
I2(1) = 1 if Surface type=B, -1 if Surface type=SMA, 0 otherwise
I2(2) = 1 if Surface type=F, -1 if Surface type=SMA, 0 otherwise

Although a relationship was determined, it explains only about 50 percent of the variability in the measurements. Given the relatively small number of samples available and the preponderance of F-mix data (37 of 47), it is recommended that the relationship not be used to estimate LASER IRI until (unless) additional information is gathered.

5.2.3 After Construction IRI Analysis

The purpose of this analysis is to determine which of the measured factors, if any, effect the after construction IRI values in a statistically significant way. The results of a general linear model analysis are discussed below. The project lengths were coded as noted above. There were 343 records available for use in this analysis.

A multi-factor analysis of variance (ANOVA) was performed using StatGraphics. It constructs various tests and graphs to determine which factors have a statistically significant effect on After IRI. It also tests for significant two-way interactions amongst the factors, given sufficient data. The F-tests in the ANOVA table will allow one to identify the significant factors. For each significant factor, the Multiple Range Tests will determine which means are significantly different.

This analysis judges the importance of a number of project-related factors on the after construction. The factors considered are shown below.

- Dependent variable: After IRI
- Factors:
  Classification – Interstate, Non-NHS, or NHS
  Surface Type – B-, C-, or F-mix
  Project Type – Inlay, Inlay-overlay, single overlay, multiple overlay or reconstruction
  Urban Rural – Urban or Rural
  Project Length – Short (0 to 2 miles), Medium (2 to 5 miles) or Long (> 5 miles)
- Number of complete cases: 343

The ANOVA table, shown in Table 5.9, decomposes the variability of improvement into contributions due to various factors. Since Type III sums of squares was chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since the P-values for all major factors are greater than 0.05, none of the major factors is statistically significant.

Table 5.9: Analysis of variance for after IRI - type III sums of squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Main Effects					
A: Classification	41122	2	20561	0.03	0.9661
B: Urban Rural	824259	1	824259	2.03	0.2551
C: Surface Type	606153	2	303076	0.79	0.4801
D: Project Type	349171	4	87292.8	0.34	0.8488
E: Project Length	859638	2	429819	3.08	0.0832
Interactions					
AB	728768	2	364384	4.22	0.0156
AC	1.25E+06	4	311677	3.61	0.0069
AD	1.29E+06	8	160947	1.86	0.0656
AE	301307	4	75326.8	0.87	0.4810
BC	518386	2	259193	3.00	0.0513
BD	316931	4	79232.7	0.92	0.4542
BE	133237	2	66618.7	0.77	0.4634
CD	2.62E+06	8	327459	3.79	0.0003
CE	1.58E+06	4	395140	4.57	0.0014
DE	976801	8	122100	1.41	0.1903
Residuals	2.46E+07	285	86372.6		
TOTAL Corrected	**4.39E+07**	**342**			

All F-ratios are based on the residual mean square error.

Some of the two-way interactions were statistically significant; for example, Classification by Urban/Rural, Classification by Surface Type, Surface Type by both Project Type and Project Length. Examination of the Table of Means, Table 5.10, demonstrates that the differences in after-construction IRI are principally due to improved measured smoothness associated with the C-mix projects. This may be attributable to the measurement tool (ultrasonic) rather than any true difference in smoothness. It is widely reported that ultrasonic measurements tend to be higher for pavement with high surface texture (i.e., F-mix). The statistical difference shown in the Classification by Urban/Rural is the result of the increased smoothness in rural interstate and NHS projects. This difference is not apparent in Non-NHS projects.

Table 5.10 shows the mean After IRI for each level of the factors. It also shows the standard error of each mean, which is a measure of its sampling variability. The rightmost two columns show 95.0% confidence intervals for each of the means.

Table5.10: Least squares means for improvement with 95.0 percent confidence intervals

Level	Count	Mean	Standard Error	Lower Limit	Upper Limit
GRAND MEAN	343	1354.54	74.2231	1208.45	1500.64
Classification					
Interstate	44	1293.0	515.9	-227.6	2813.6
NHS	189	1398.3	121.1	1041.4	1755.1
Non NHS	110	1372.4	140.2	959.2	1785.5
Surface_Type					
B	114	1418.8	118.3	1157.5	1680.2
C	64	1147.6	330.5	417.7	1877.5
F	165	1497.2	164.1	1134.9	1859.6
Project_Type					
Inlay	39	1255.3	156.8	911.0	1599.7
RECONST	34	1365.6	277.9	755.3	1975.9
inlay-overlay	90	1396.7	145.6	1076.8	1716.5
overlay multiple	83	1369.9	164.3	1009.1	1730.8
overlay single	97	1385.2	111.6	1140.2	1630.3
Urban_Rural					
Rural	253	1250.8	186.1	634.3	1867.4
Urban	90	1458.3	166.3	907.3	2009.2
Project Length					
Long	126	1144.1	111.1	902.1	1386.0
Medium	128	1272.4	86.0	1085.0	1459.7
Short	89	1647.2	195.7	1220.7	2073.7
Classification by Surface_Type					
Interstate B	8	1428.4	144.5	1144.0	1712.9
Interstate C	1	917.0	441.5	48.0	1786.0
Interstate F	35	1533.5	183.3	1172.7	1894.3
NHS B	69	1523.2	51.9	1421.1	1625.3
NHS C	28	1200.2	73.7	1055.1	1345.3
NHS F	92	1471.5	67.7	1338.3	1604.6
Non NHS B	37	1304.8	69.1	1168.8	1440.9
Non NHS C	35	1325.5	67.3	1193.1	1457.9
Non NHS F	38	1486.8	91.5	1306.6	1666.9
Classification by Project_Type					
Interstate Inlay	10	1180.2	242.5	702.9	1657.5
Interstate RECONST	1	1550.1	491.7	582.3	2517.8
Interstate inlay-overlay	17	1362.8	200.7	967.7	1758.0
Interstate overlay multiple	8	1205.0	219.1	773.7	1636.2
Interstate overlay single	8	1166.8	149.0	873.6	1460.0
NHS Inlay	21	1233.6	75.5	1085.0	1382.1
NHS RECONST	17	1154.6	147.0	865.4	1443.9
NHS inlay-overlay	54	1552.3	56.0	1442.0	1662.6
NHS overlay multiple	43	1507.1	78.4	1352.8	1661.5
NHS overlay single	54	1543.8	62.5	1420.8	1666.8
Non-NHS Inlay	8	1352.2	142.5	1071.6	1632.7
Non-NHS RECONST	16	1392.0	129.1	1137.8	1646.2
Non-NHS inlay-overlay	19	1274.8	78.1	1121.1	1428.6
Non-NHS overlay multiple	32	1397.7	79.9	1240.4	1555.1
Non-NHS overlay single	35	1445.1	71.8	1303.8	1586.4

Level		Count	Mean	Standard Error	Lower Limit	Upper Limit
Classification by Urban/Rural						
Interstate	Rural	35	1135.6	240.1	663.0	1608.3
Interstate	Urban	9	1450.3	191.6	1073.1	1827.5
NHS	Rural	141	1239.9	50.0	1141.5	1338.3
NHS	Urban	48	1556.7	72.1	1414.8	1698.6
Non NHS	Rural	77	1377.0	54.0	1270.8	1483.2
Non NHS	Urban	33	1367.8	87.3	1196.0	1539.5
Classification by Project Length						
Interstate	Long	31	1091.0	152.1	791.7	1390.4
Interstate	Medium	11	1106.4	168.3	775.1	1437.6
Interstate	Short	2	1681.5	439.8	815.7	2547.3
NHS	Long	69	1176.0	103.8	971.6	1380.3
NHS	Medium	75	1335.8	52.3	1232.9	1438.6
NHS	Short	45	1683.1	50.5	1583.6	1782.6
Non NHS	Long	26	1165.1	112.0	944.7	1385.6
Non NHS	Medium	42	1375.0	65.6	1245.9	1504.2
Non NHS	Short	42	1576.9	58.7	1461.4	1692.5
Surface_Type by Project_Type						
B	Inlay	17	1295.8	94.7	1109.3	1482.3
B	RECONST	15	1574.7	127.1	1324.5	1824.9
B	inlay-overlay	21	1351.0	97.8	1158.4	1543.6
B	overlay multiple	26	1494.9	96.9	1304.2	1685.7
B	overlay single	35	1377.6	85.3	1209.7	1545.6
C	Inlay	12	981.2	205.7	576.3	1386.0
C	RECONST	9	770.3	241.9	294.1	1246.6
C	inlay-overlay	13	1461.2	180.7	1105.4	1816.9
C	overlay multiple	7	1144.4	194.4	761.8	1526.9
C	overlay single	23	1380.9	137.5	1110.2	1651.6
F	Inlay	10	1489.0	135.3	1222.7	1755.2
F	RECONST	10	1751.7	210.5	1337.3	2166.1
F	inlay-overlay	56	1377.8	77.8	1224.6	1530.9
F	overlay multiple	50	1470.5	85.6	1302.1	1638.9
F	overlay single	39	1397.2	84.2	1231.3	1563.0
Surface_Type by Urban_Rural						
B	Rural	80	1279.6	68.2	1145.3	1413.8
B	Urban	34	1558.1	81.4	1397.9	1718.3
C	Rural	28	979.3	185.5	614.1	1344.5
C	Urban	36	1315.9	149.1	1022.4	1609.3
F	Rural	145	1493.7	69.9	1356.0	1631.3
F	Urban	20	1500.8	105.0	1294.0	1707.5
Surface_Type by Project Length						
B	Long	40	1292.8	102.0	1092.0	1493.6
B	Medium	38	1350.8	90.0	1173.7	1527.8
B	Short	36	1612.9	124.2	1368.3	1857.5
C	Long	13	810.0	168.5	478.4	1141.6
C	Medium	27	955.7	142.1	676.1	1235.3
C	Short	24	1677.0	240.2	1204.3	2149.7
F	Long	73	1329.4	96.9	1138.7	1520.1
F	Medium	63	1510.7	81.3	1350.8	1670.6
F	Short	29	1651.6	151.7	1353.0	1950.2

Level		Count	Mean	Standard Error	Lower Limit	Upper Limit
Project_Type by Urban_Rural						
Inlay	Rural	19	1157.9	126.8	908.4	1407.5
Inlay	Urban	20	1352.7	104.0	1148.0	1557.4
RECONST	Rural	18	1225.5	158.6	913.2	1537.8
RECONST	Urban	16	1505.7	190.2	1131.3	1880.0
inlay-overlay	Rural	68	1339.2	113.5	1115.8	1562.6
inlay-overlay	Urban	22	1454.1	95.4	1266.3	1641.9
overlay multiple	Rural	67	1189.6	101.3	990.1	1389.0
overlay multiple	Urban	16	1550.3	122.4	1309.4	1791.3
overlay single	Rural	81	1342.0	79.8	1185.0	1499.0
overlay single	Urban	16	1428.5	88.6	1254.2	1602.8
Project_Type by Project Length						
Inlay	long	11	1167.2	119.5	932.1	1402.4
Inlay	medium	18	1180.3	88.0	1007.2	1353.5
Inlay	short	10	1418.4	199.4	1025.9	1810.8
Reconst	long	2	791.6	260.1	279.6	1303.6
Reconst	medium	7	1416.9	233.5	957.2	1876.6
Reconst	short	25	1888.2	244.0	1407.9	2368.5
Inlay overlay	long	48	1251.9	90.9	1073.0	1430.8
Inlay overlay	medium	32	1199.0	86.2	1029.3	1368.7
Inlay overlay	short	10	1739.1	188.6	1367.9	2110.3
Overlay multiple	long	36	1283.6	115.2	1056.8	1510.4
Overlay multiple	medium	26	1231.1	102.7	1029.0	1433.2
Overlay multiple	short	21	1595.1	162.3	1275.7	1914.5
Overlay single	long	29	1225.9	101.4	1026.3	1425.5
Overlay single	medium	45	1334.6	73.3	1190.4	1478.8
Overlay single	short	23	1595.1	125.3	1348.4	1841.8
Urban_Rural by Project Length						
Rural	Long	118	1030.2	77.2	878.3	1182.1
Rural	Medium	96	1208.8	78.0	1055.3	1362.3
Rural	Short	39	1513.5	190.2	1139.1	1887.9
Urban	Long	8	1257.9	133.8	994.5	1521.4
Urban	Medium	32	1336.0	82.6	1173.4	1498.6
Urban	Short	50	1780.9	134.8	1515.6	2046.1

5.2.4 Percent Improvement Analysis

The purpose of this analysis was to determine which of the measured factors, if any, effect the percent improvement in IRI values in a statistically significant way. The percent improvement is calculated as the Before Construction IRI, minus the After Construction IRI, divided by the Before Construction IRI, and expressed as a percentage. The results of a general linear model analysis are discussed in the following section. The project lengths were coded as noted above. Before Construction IRI data were not available for all the sections, therefore, only 239 records were available for use in this analysis.

A multi-factor analysis of variance (ANOVA) was performed using StatGraphics. It constructs various tests and graphs to determine which factors have a statistically significant effect on Percent Improvement. It also tests for significant two-way interactions amongst the factors, given sufficient data. The F-tests in the ANOVA table will allow one to identify the significant factors. For each significant factor, the Multiple Range Tests will determine which means are significantly different. Results are shown in Table 5.11. The factors considered are shown below:

- Dependent variable: Improvement
- Factors:
    Classification – Interstate, Non-NHS, or NHS
    Surface Type – B-, C-, or F-mix
    Project Type – Inlay, Inlay-overlay, single overlay, multiple overlay or reconstruction
    Urban Rural – Urban or Rural
    Project Length – Short (0 to 2 miles), Medium (2 to 5 miles) or Long (> 5 miles)
- Number of complete cases: 239

Table 5.11: Analysis of variance for percent improvement – type III sums of squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Main Effects					
A: Classification	2923.9	2	1461.95	1.30	0.3995
B: Urban Rural	214.673	1	214.673	0.25	0.6481
C: Surface Type	1467.12	2	733.559	3.34	0.0970
D: Project Type	2068.34	4	517.086	2.17	0.2957
E: Project Length	632.408	2	316.204	0.52	0.6482
Interactions					
AB	1751.42	2	875.71	5.22	0.0062
AC	1757.48	4	439.369	2.62	0.0362
BC	318.009	2	159.004	0.95	0.3891
BD	821.351	4	205.338	1.22	0.3016
BE	1320.47	2	660.235	3.94	0.0211
CD	683.46	8	85.4324	0.51	0.8483
CE	692.03	4	173.007	1.03	0.3919
DE	2264.73	8	283.092	1.69	0.1032
Residuals	32352.3	193	167.629		
TOTAL Corrected	**54425.2**	**238**			

Number of dependent variables: 1
Number of categorical factors: 5
Number of quantitative factors: 0

As can be seen, in Table 5.11, none of the main effects are statistically significant at the 5 percent level. Some of the two-way interactions were significant at the five percent level (note that interactions AD and AE were not possible due to insufficient data) including Classification by Urban/Rural, Classification by Surface Type and Urban/Rural by Project Length.

Table 5.12 shows the mean for Improvement for each level of the factors. It also shows the standard error of each mean, which is a measure of its sampling variability. The rightmost two columns show 95.0% confidence intervals for each of the means

Table 5.12: Least squares means for improvement with 95.0 percent confidence intervals

Level	Count	Mean	Standard Error	Lower Limit	Upper Limit
GRAND MEAN	239	34.1	2.5	29.1	39.1
Classification					
Interstate	27	41.1	15.3	-10.0	92.3
NHS	136	26.2	6.0	6.4	46.1
Non NHS	76	34.9	6.7	12.8	57.1
Surface_Type					
B	87	38.2	4.1	28.5	47.9
C	54	37.9	6.8	21.8	54.0
F	98	26.3	3.4	18.2	34.3
Project_Type					
Inlay	33	35.8	4.1	21.6	50.0
RECONST	12	44.4	7.7	17.8	71.1
inlay-overlay	68	27.3	3.7	14.4	40.2
overlay multiple	62	33.4	4.1	19.3	47.5
overlay single	64	29.6	3.7	16.9	42.3
Urban_Rural					
Rural	180	32.0	7.0	12.0	52.0
Urban	59	36.2	7.4	15.1	57.3
Project Length					
Long	101	33.1	8.9	2.0	64.2
Medium	87	38.0	6.3	16.1	59.9
Short	51	31.2	5.4	12.4	50.1
Classification by Surface_Type					
Interstate B	4	54.3	9.2	36.2	72.5
Interstate C	1	39.9	15.9	8.4	71.3
Interstate F	22	29.2	4.5	20.2	38.1
NHS B	56	26.6	2.7	21.2	32.0
NHS C	24	35.7	3.6	28.5	42.9
NHS F	56	16.4	3.8	9.0	23.9
Non NHS B	27	33.6	3.6	26.6	40.7
Non NHS C	29	38.0	3.4	31.4	44.7
Non NHS F	20	33.2	4.6	24.1	42.2
Classification by Urban/Rural					
Interstate Rural	22	31.6	7.2	17.4	45.8
Interstate Urban	5	50.7	8.0	34.8	66.5
NHS Rural	104	30.8	2.4	26.1	35.5
NHS Urban	32	21.7	3.7	14.4	28.9
Non NHS Rural	54	33.6	2.5	28.7	38.5
Non NHS Urban	22	36.3	4.2	28.0	44.5
Surface_Type by Project_Type					
B Inlay	15	37.9	4.0	29.9	45.8
B RECONST	5	55.0	9.2	36.9	73.1
B inlay-overlay	19	29.8	4.7	20.5	39.1
B overlay multiple	22	34.2	4.6	25.2	43.1
B overlay single	26	34.1	4.9	24.3	43.8
C Inlay	12	42.4	7.9	26.8	58.0

Level		Count	Mean	Standard Error	Lower Limit	Upper Limit
C	RECONST	4	43.7	11.7	20.7	66.7
C	inlay-overlay	13	31.9	7.2	17.7	46.1
C	overlay multiple	7	37.2	7.6	22.2	52.1
C	overlay single	18	34.2	5.8	22.7	45.7
F	Inlay	6	27.2	7.0	13.3	41.0
F	RECONST	3	34.5	9.2	16.4	52.6
F	inlay-overlay	36	20.2	3.4	13.5	26.9
F	overlay multiple	33	29.0	3.3	22.4	35.6
F	overlay single	20	20.5	4.2	12.2	28.7
Surface_Type by Urban_Rural						
B	Rural	68	33.7	3.2	27.4	40.0
B	Urban	19	42.7	5.5	31.9	53.6
C	Rural	25	35.5	7.8	20.0	50.9
C	Urban	29	40.3	5.5	29.4	51.2
F	Rural	87	26.9	2.6	21.8	32.0
F	Urban	11	25.6	4.9	15.9	35.3
Surface_Type by Project Length						
B	Long	36	37.8	5.8	26.4	49.2
B	Medium	30	41.8	4.1	33.6	50.0
B	Short	21	34.9	4.3	26.5	43.4
C	Long	13	40.3	7.8	25.0	55.7
C	Medium	25	43.0	6.5	30.2	55.8
C	Short	16	30.3	7.1	16.3	44.2
F	Long	52	21.2	5.0	11.4	31.0
F	Medium	32	29.2	4.6	20.1	38.2
F	Short	14	28.4	4.2	20.1	36.7
Project_Type by Urban_Rural						
Inlay	Rural	15	29.2	5.2	19.1	39.4
Inlay	Urban	18	42.4	5.6	31.4	53.4
RECONST	Rural	6	41.4	7.5	26.6	56.1
RECONST	Urban	6	47.4	8.4	31.0	63.9
inlay-overlay	Rural	50	23.8	4.4	15.0	32.6
inlay-overlay	Urban	18	30.8	4.4	22.3	39.4
overlay multiple	Rural	52	37.0	3.4	30.4	43.7
overlay multiple	Urban	10	29.9	5.4	19.3	40.4
overlay single	Rural	57	28.6	3.1	22.4	34.8
overlay single	Urban	7	30.5	5.4	20.0	41.1
Project_Type by Project Length						
Inlay	long	8	39.2	5.7	27.9	50.5
Inlay	medium	16	38.9	4.2	30.6	47.1
Inlay	short	9	29.3	5.5	18.4	40.2
Reconst	long	1	39.9	16.7	7.0	72.8
Reconst	medium	2	49.6	12.2	25.4	73.7
Reconst	short	9	43.8	5.0	33.8	53.7
Inlay overlay	long	38	32.3	4.2	24.1	40.6
Inlay overlay	medium	23	35.4	3.6	28.3	42.5
Inlay overlay	short	7	14.2	5.9	2.5	25.9

Level		Count	Mean	Standard Error	Lower Limit	Upper Limit
Overlay multiple	long	30	30.6	5.3	20.0	41.1
Overlay multiple	medium	19	31.5	4.7	22.2	40.8
Overlay multiple	short	13	38.2	4.2	29.9	46.6
Overlay single	long	24	23.6	4.7	14.3	32.8
Overlay single	medium	27	34.7	3.4	27.9	41.5
Overlay single	short	13	30.5	5.1	20.4	40.5
Urban_Rural by Project Length						
Rural	Long	94	37.5	4.2	29.1	45.8
Rural	Medium	63	32.7	3.9	25.0	40.5
Rural	Short	23	25.8	4.7	16.6	35.0
Urban	Long	7	28.7	6.7	15.5	42.0
Urban	Medium	24	43.3	4.0	35.3	51.3
Urban	Short	28	36.6	4.2	28.3	44.9

Three of the two-way interactions are statistically significant; Classification by Urban/Rural, Classification by Surface Type and Urban/Rural by Project Length. Examining the Before Construction IRI, as seen in Table 5.13, and the associated interaction plots assists in understanding the significance of these interactions.

Table 5.13: Before and after IRI for classification by rural/urban two-way interaction

Project Type	Number of Projects	Average Before IRI, mm/km	Average After IRI, mm/km
Interstate - Rural	22	1743.4	1269.8
Interstate - Urban	5	1903.8	1250.0
NHS - Rural	104	1893.1	1336.0
NHS - Urban	32	2237.7	1584.7
Non NHS - Rural	54	2126.7	1366.5
Non NHS - Urban	22	2419.8	1424.1

As shown in Figure 5.2, much of the differences in percent improvement are attributable to the higher, before construction, roughness of the sections, irrespective of the road classification.

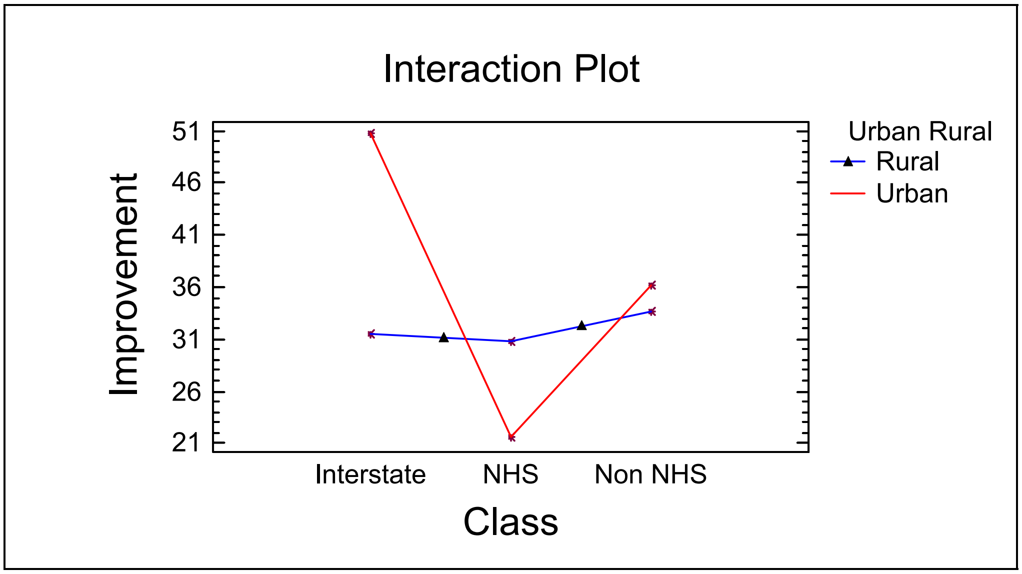

Figure 5.2: Effect of road classification on percent improvement in ride quality

Table 5.14: Before and after IRI for classification by surface type two-way interaction

Project Type	Number of Projects	Average Before IRI, mm/km	Average After IRI, mm/km
Interstate B	4	1965.5	1075.0
Interstate C	1	1863.0	850.0
Interstate F	22	1734.0	1319.8
NHS B	56	2002.6	1407.9
NHS C	24	2136.8	1349.2
NHS F	56	1876.1	1400.5
Non NHS B	27	1970.1.2	1295.6
Non NHS C	29	2377.1	1419.7
Non NHS F	20	2297.4	1448.5

The interaction plot in Figure 5.3 was prepared from Table 5.14 and suggests that for NHS and Non-NHS projects, C-mixes yield the greatest percent improvement. This is not the case for Interstate projects, but since only one project is included in the data set this result may not be valid.

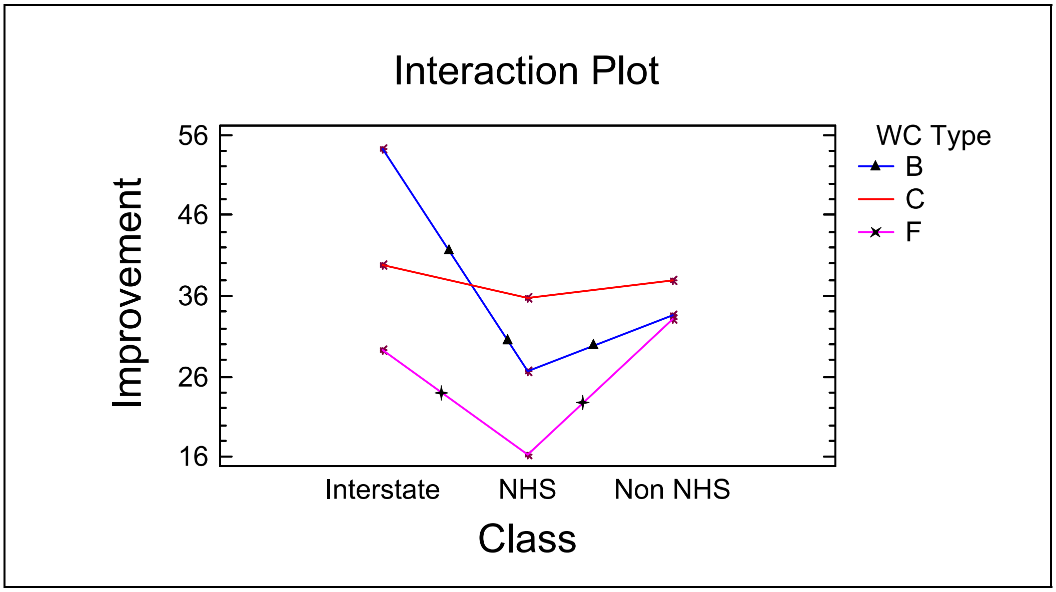

Figure 5.3: Effect of wearing course mix type on ride quality improvement

Table 5.15: Before and after IRI for rural/urban by project length two-way interaction

Project Type	Number of Projects	Average Before IRI, mm/km	Average After IRI, mm/km
Rural Long	94	1854.8	1269.5
Rural Medium	63	2001.4	1402.0
Rural Short	23	2158.4	1435.2
Urban Long	7	1838.6	1355.7
Urban Medium	24	2208.0	1306.3
Urban Short	28	2446.4	1694.6

The interaction plot, Figure 5.4 developed from Table 5.15, shows that increasing the length of the projects results in a greater increase in the percent improvement for rural projects, but not for urban projects. It should be noted that only seven urban projects were constructed that were longer than 6 miles.

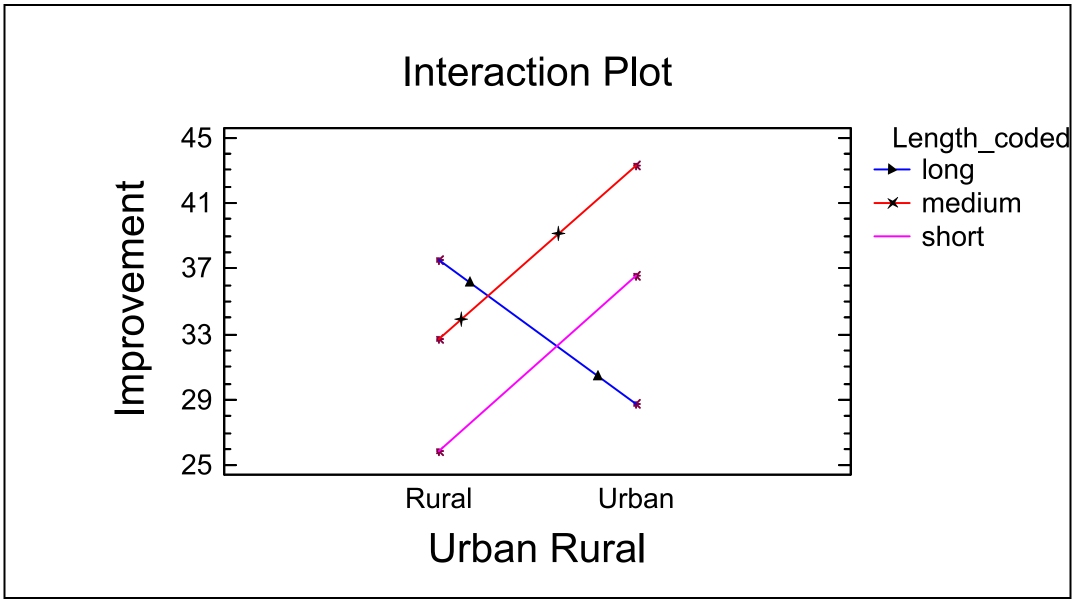

Figure 5.4: Effect of project length on percent ride improvement

5.3 SUMMARY

5.3.1 Laser and Ultrasonic IRI Relationship

The overall average difference between laser-based IRI and profilometer-based IRI was approximately 230 mm/km (laser-based IRI values are lower).

A relationship was defined that is able to predict Laser IRI from surface type, profiler and project length; however, only about one-half the variability present in the available data is explained. The usefulness of the relationship is limited to B- or F-mixes and the four profilers used in the original data set. Additional data should be gathered to improve the robustness of the relationship and expand the inference space.

The difference between laser-based and profilometer-based IRI measurements taken on F- and B-mix projects after construction was investigated. The goal was to determine whether the open texture of the F-mixes adversely affected the reported IRI values. This was analyzed by comparing the laser- and profilometer-based IRI values for F-mixes and B-mixes separately when only one laser profiler was used. For the limited data set available, no statistically significant differences could be found between laser-based and profilometer-based IRI measurements.

5.3.2 After Construction IRI and Percent Improvement in IRI

The goal was to determine whether there are statistically significant differences in ride quality after construction resulting from various types of asphalt rehabilitation projects. None of the main effects appears to have any statistically significant effect on the measured smoothness after construction. Some of the two-way interactions are statistically significant; however the apparent differences may be due more to the measurement device (ultrasonic) than any true differences in smoothness. This hypothesis could not be tested with the available data.

Percent improvement (expressed as a reduction in IRI, as a percent of initial IRI) resulting from various types of asphalt rehabilitation projects was also investigated. Data from 239 projects were available for this analysis. The overall percent improvement for all project types is 34 percent. Again none of the main effects are statistically significant.

5.4 IMPLEMENTATION

5.4.1 General

ODOT currently has a ride specification based on the Profile Index, as measured by a California Profilograph. The intent is to implement a specification based on the International Roughness Index (IRI). The data evaluated in this research was intended to assist in developing the appropriate IRI specifications and price adjustment criteria.

The original intent was to develop a correlation between ultrasonic IRI and laser IRI to enable ODOT to use data back to 1994 to establish hard IRI criteria for smoothness for all highway facilities. The conclusion of the research is that the established correlation was not robust enough to apply, with a reasonable level of confidence. This led ODOT to ask the researchers to look at percent improvement as a criterion. This would then eliminate the need for an ultrasonic/laser correlation.

ODOT transitioned from an ultrasonic profiler to a laser profiler during 2003. Measurements were obtained on several Interstate projects constructed during 2002 and 2003. The data from these projects were compared with IRI specifications from other states. ODOT's data compared well with what other state's expectations are of their paving contractors. Based on this data, and the laser data from Data Set B (Section 5.2), ODOT decided to set up separate hard IRI criteria for Interstate projects. ODOT will continue to collect and summarize laser IRI data to evaluate the possibility of moving from percent improvement to a hard IRI number for Non-Interstate facilities.

The proposed draft smoothness specification is presented in Appendix C. The specification has not gone through the formal ODOT/Paving Industry committee review process to date. It is expected that the specifications will be improved and refined through that process before a final specification is implemented.

5.4.2 Non-Interstate Projects

The research recommended no differentiation of specification requirements, based on the statistical analysis of the percent improvement data. Thus, all Non-Interstate projects will be under one specification. Percent improvement data are available for 214 non-interstate projects. The projects were sorted by percent improvement and two graphs were generated to assist in developing the specification limits. Figure 5.5 is a frequency histogram showing the distribution of percent improvement. Figure 5.6 shows each individual project in a continuous plot from lowest to highest percent improvement.

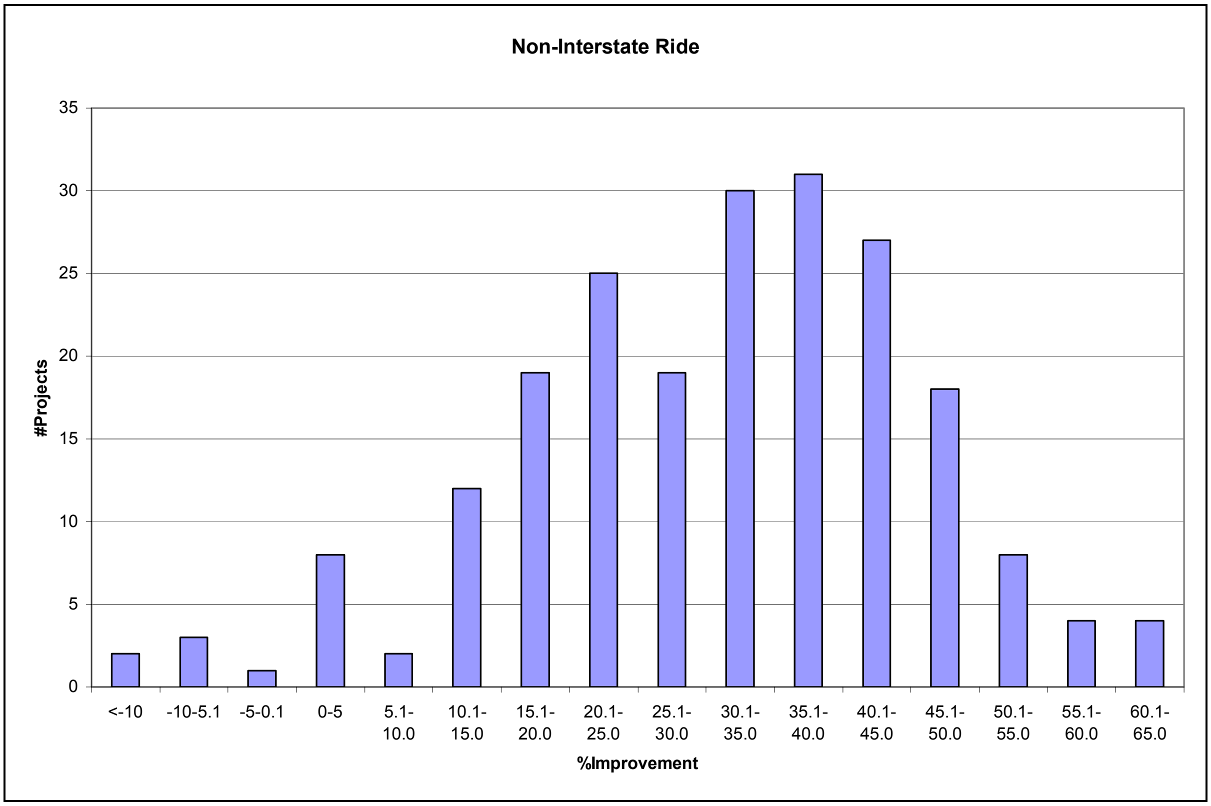

Figure 5.5: Percent improvement

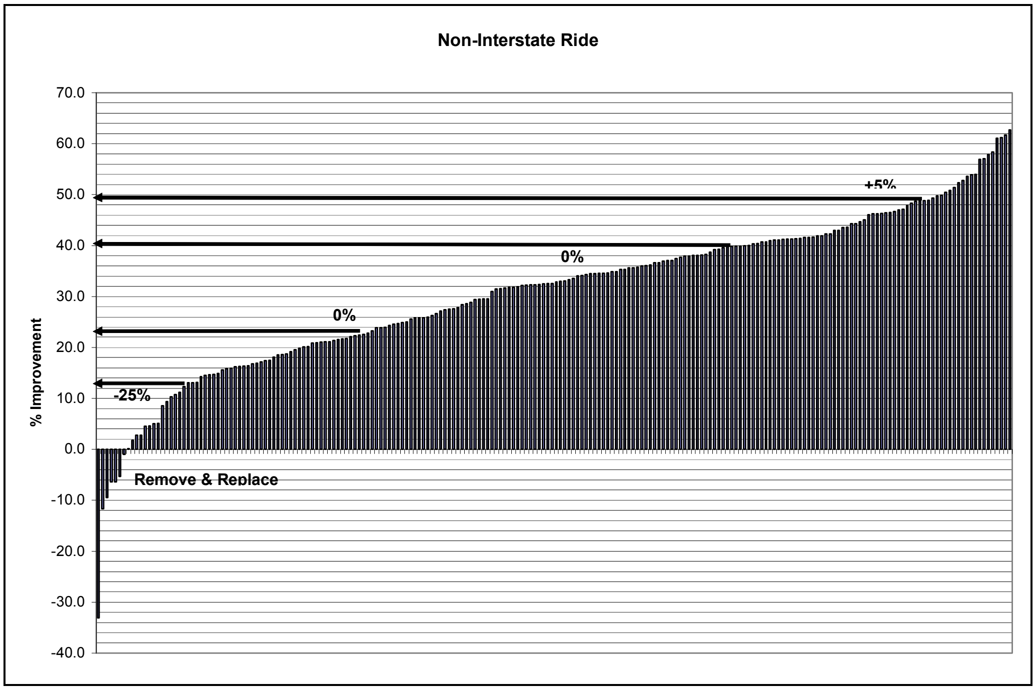

Figure 5.6: Individual projects-percent improvement

The summary statistics for all non-interstate projects are shown in Table 5.16.

Table 5.16: Summary statistics for Non-Interstate projects

Result	Corresponding % Improvement
Average	30.8
Standard Deviation	15.3
Median	32.7
10th percentile	13.1
20th percentile	18.5
30th percentile	23.2
70th percentile	39.9
80th percentile	42.3
90th percentile	48.8

The 10th, 30th, 70th, and 90th percentiles were selected as break points in the proposed specification presented in Table 5.17. These points are identified graphically in Figure 5.6. These points were selected as an initial points for the proposed specification, and were chosen because, 1) they are within the ranges that contractors have been able to achieve on ODOT projects, and 2) only ten percent of the projects would have received full bonus. It sets a reasonable level for contractors to try and improve their process to achieve a larger bonus.

Table 5.17: Non-Interstate price calculation

Percent Improvement	Contract Unit Price Adjustment
49.0 or More	+ 5.0%
40.1 to 48.9	+ 5.0% - [0.556 x (49.0 – PI)]%
23.0 to 40.0	None
13.0 to 22.9	-2.500 x (23.0 – PI)%
0.0 to 12.9	- 25.0%
Less than 0.0	Remove and Replace

5.4.3 Interstate

A review of other state's IRI specifications was conducted to determine what appropriate standards can be expected of ODOT contractors. Based on that review, the specification shown in Table 5.18 was developed.

Table 5.18: Interstate price adjustment

IRI (inch/mile)	Contract Unit Price Adjustment
45.0 or Less	+ 5.0%
45.1 to 54.9	+ 0.5 x (55.0 - IRI)%
55.0 to 70.0	None
70.1 to 99.9	0.833 x (70.0 – IRI)%
100.0 or More	- 25.0%

Several Interstate projects constructed during 2002 and 2003 were measured for IRI with ODOT's new laser profiler to determine if ODOT contractors are achieving IRI within the ranges of the proposed specification. If so, then it would be appropriate to apply a hard IRI specification to Interstate projects as they are typically relatively smooth prior to paving. Interstate projects don't have many of the issues that non-interstate projects have where the initial roughness can be substantial and a hard IRI specification is not appropriate. The results are presented in Table 5.19.

Table 5.19: Average IRI data from 2002 and 2003 Interstate projects

Project	MixType	Average IRI (in/mile)
A	C	58.9
B	B	62.1
C	SMA	51.3
D	F	71.3
E	F	65.2
F	SMA	52.2
G	F	68
H	SMA	59.6
I	B	57.95
J	F	74.4
K	F	68.7
L	SMA	48.1
M	F	52.4
N	F	70.3

The results from Table 5.19 show that ODOT contractors are providing smoothness values within the ranges expected by other states. The results also show that the price adjustment, shown in Table 5.18, is a reasonable starting point for building a specification.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This project evolved significantly over the course of the research. Two principal specification-related products were produced and are available for ODOT's implementation. As with many changes in specifications, ODOT will proceed with implementation after careful review and discussion with all stakeholders including contractors and producers. The first product allows ODOT to statistically judge the HMA quality using the loss function and rewards contractors for mix low variability and adherence to the job mix targets. Second, data analyses showed that project smoothness, as measured by IRI, could be incorporated into an ODOT specification, but only in the form of percent improvement in ride over the existing roadway. Additional data will have to be collected before a set value of IRI can be specified for projects.

Specific conclusions and recommendations associated with this project include:

1. The loss function can be adapted to use with hot mix asphalt quality control specifications and effectively rewards contractors that consistently produce mix on target with minimal variability.

2. The loss function presented in this report can be easily modified to incorporate other mix factors, should ODOT decide to modify the loss function.

3. Full implementation of the loss function will require that ODOT collect additional information and develop a pilot implementation plan.

4. Analyses of the available smoothness data indicates that a minimum level of IRI cannot be specified until additional information is collected using laser-based technology.

5. Until the above data collection is complete, specified project smoothness should be based on percent improvement.

7.0 IMPLEMENTATION

ODOT will be using the results of this research to implement an improved specification for HMA acceptance. Draft specifications will be developed through interaction with ODOT/Paving Industry committees in 2004 taking into consideration data collected since the researchers completed their work in 2002/2003. It is anticipated that a future report will be published that summarizes the work of the committees and experience with trial projects.

As noted in Section 5.0, ODOT has already collected enough additional laser profiler data to move ahead with a hard IRI draft specification for interstate projects, but keeping percent improvement for non-interstate projects as recommended by the researchers.

An Excel workbook was created to automate the pay factor calculations. It is expected that the workbook, modified as necessary to reflect any changes in a draft specification, will be incorporated into ODOT contract administration practices for computing price adjustments for HMA mixtures.

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APPENDICES

APPENDIX A

MODEL AND NOTATION

k - Factor index ($k = 1, \ldots f$)

j - Target index within k^{th} factor ($j = 1, \ldots, jMax$)

i - Measurement index within j^{th} target within k^{th} factor ($i = 1, \ldots, t$)

$jMax_k$ - Total number of target changes for k^{th} factor

t_{jk} - Total number of measurements for j^{th} target within k^{th} factor

n_k - Total number of measurements for k^{th} factor

X_{ijk} - i^{th} measurement within j^{th} target within k^{th} factor

T_{jk} - j^{th} target within k^{th} factor

$\overline{X}_{jk} = \sum_{i=1}^{t_{jk}} X_{ijk}$ - Average of the measurements for j^{th} target within k^{th} factor

$\Delta_{jk} = \left(\overline{X}_{jk} - T_{jk}\right)^2$ - Closeness to target measure for j^{th} target within k^{th} factor

$S_{jk}^2 = \frac{1}{t_{jk} - 1} \sum_{i=1}^{t_{jk}} \left(X_{ijk} - \overline{X}_{jk}\right)^2$ - Variability measure (sample variance) for j^{th} target within k^{th} factor

$\overline{\Delta}_k = \frac{1}{n_k} \sum_{j=1}^{jMax_k} t_{jk} \Delta_{jk}$ - Weighted average of closeness to target measure for k^{th} factor

$\overline{S_k^2} = \frac{1}{n_k} \sum_{j=1}^{jMax_k} t_{jk} S_{jk}^2$ - Weighted average of variability measure for k^{th} factor

f - Total number of factors

w_k - Weight for relative importance of k^{th} factor

$PF_{k,\Delta}$ - Individual pay factor for closeness to target measure of k^{th} factor

$PF_{k,S}$ - Individual pay factor for variability measure of k^{th} factor

$V_\Delta = \sum_{k=1}^{f} w_k \, PF_{k,\Delta}$ - Intermediate "pay factor" value of closeness to target over all factors

$V_S = \sum_{k=1}^{f} w_k \, PF_{k,S}$ - Intermediate "pay factor" value of variability over all factors

$V_k = w_k \left(PF_{k,\Delta} + PF_{k,S}\right)$ - Intermediate "pay factor" value of k^{th} factor for closeness to target and variability

$PF = \frac{1}{f}\sum_{k=1}^{f} V_k$ - Composite pay factor for lot

APPENDIX B

ULTRASONIC- AND LASER-BASED IRI VALUES PROJECTS COMPLETED IN 1999 AND 2000

Contract	Highway	Year	Lane	Contractor	Wearing Course Type	Profiler ID	Mean Laser IRI	STDEV IRI	Mean Ultrasonic IRI	STDEV Ultrasonic IRI	Mean PI	STDEV PI	Percent Difference
C12101	1	1998	NBRight	JC Compton	F	JCC1	988	132	1118	133	14	20	11.6
C12101	1	1998	SBRight	JC Compton	F	JCC1	979	107	1307	113	14	18	25.1
C12119	1	1998	SBRight	Morse Bros	F	MBI1	924	137	1249	107	20	26	26.0
C12119	1	1998	NBRight	Morse Bros	F	MBI1	894	160	1216	144	16	18	26.5
C12155	1	1999	NBFast	JC Compton	F	JCC1	1101	138	1106	175	25	31	0.5
C12155	1	1999	SBRight	JC Compton	F	JCC1	1156	160	1204	195	20	20	4.0
C12181	1	1999	NBLeft	Morse Bros	F	MBI1	1088	193	1156	153	92	93	5.9
C12155	1	1999	NBRight	JC Compton	F	JCC1	1101	121	1190	188	25	30	7.5
C12155	1	1999	SBFast	JC Compton	F	JCC1	1075	155	1208	268	22	26	11.0
C12265	91	1999	SB	JC Compton	F	JCC1	1033	244	1164	212	49	55	11.3
C12265	91	1999	NB	JC Compton	F	JCC1	1022	302	1162	246	38	42	12.0
C12243	42	1999	SB	JC Compton	F	JCC1	1095	176	1274	114	33	26	14.1
C12243	42	1999	NB	JC Compton	F	JCC1	1112	176	1306	124	43	32	14.9
C12252	4	1999	NB	JC Compton	F	JCC1	1134	116	1358	108	19	19	16.5
C12252	4	1999	SB	JC Compton	F	JCC1	1151	102	1381	111	23	24	16.7
C12181	1	1999	SBRight	Morse Bros	F	MBI1	986	127	1200	117	57	50	17.8
C12126	2	1999	WB	JC Compton	F	JCC1	1073	135	1312	148	18	28	18.2
C12221	1	1999	SBFast	LTM	F	LTM1	961	107	1192	163	40	37	19.4
C12181	1	1999	NBRight	Morse Bros	F	MBI1	941	110	1181	115	36	40	20.3
C12126	2	1999	EB	JC Compton	F	JCC1	988	106	1261	156	11	24	21.6
C12181	1	1999	NBCenter	Morse Bros	F	MBI1	872	152	1163	266	31	52	25.0
C12221	1	1999	NBFast	LTM	F	LTM1	941	124	1286	167	34	41	26.8
C12181	1	1999	SBLeft	Morse Bros	F	MBI1	873	91	1204	133	27	25	27.5
C12181	1	1999	SBCenter	Morse Bros	F	MBI1	916	86	1289	158	21	32	28.9
C12221	1	1999	NBRight	LTM	F	LTM1	827	98	1255	202	16	26	34.1
C12221	1	1999	SBRight	LTM	F	LTM1	758	93	1204	178	11	22	37.0
C12324	2	2000	EBFast	JC Compton	F	JCC1	1333	136	1291	88	19	22	-3.3
C12324	2	2000	WBRight	JC Compton	F	JCC1	1155	136	1200	108	12	17	3.8
C12324	2	2000	WBFast	JC Compton	F	JCC1	1262	99	1336	89	17	25	5.5
C12324	2	2000	EBRight	JC Compton	F	JCC1	1109	108	1235	98	10	19	10.2
C12345	162	2000	WB	JC Compton	B	JCC1	953	143	1083	556	40	28	12.0
C12363	91	2000	SBFast	Morse Bros	F	BY1	1051	137	1202	105	38	34	12.6
C12369	53	2000	EB	JC Compton	F	JCC1	1253	99	1448	132	66	36	13.5
C12363	91	2000	NBFast	Morse Bros	F	BY1	1126	139	1303	153	42	42	13.6
C12345	162	2000	WB	JC Compton	B	JCC1	1012	154	1200	167	64	41	15.7
C12345	162	2000	EB	JC Compton	B	JCC1	1077	183	1290	193	92	58	16.5
C12347	35	2000	WB	Roseburg Paving	B	JCC1	1069	287	1303	350	72	77	18.0
C12269	6	2000	WBRight	JC Compton	SMA	JCC1	837	102	1040	215	17	26	19.5
C12345	162	2000	EB	JC Compton	B	JCC1	922	187	1157	223	54	34	20.3
C12363	91	2000	NBRight	Morse Bros	F	BY1	991	120	1249	130	33	45	20.7
C12363	91	2000	SBRight	Morse Bros	F	BY1	875	165	1160	198	26	68	24.6
C12369	53	2000	WBPass	JC Compton	F	JCC1	1036	86	1429	121	36	33	27.5
C12357	162	2000	EB	Morse Bros	B	MBI1	1071	201	1488	238	142	75	28.0
C12347	35	2000	EB	Roseburg Paving	B	JCC1	1062	300	1477	355	86	70	28.1
C12369	53	2000	WBRight	JC Compton	F	JCC1	1058	126	1495	125	42	44	29.2
C12357	162	2000	WB	Morse Bros	B	MBI1	937	207	1346	221	94	64	30.4
C12269	6	2000	EBRight	JC Compton	SMA	JCC1	839	120	1454	109	18	25	42.3
C12348	22	2000	EB	LTM	B	LTM1			1108	274			
C12348	22	2000	WB	LTM	B	LTM1			1161	236			
C12420	9	2000	NB	McCafferty-Whittle	C	MW1			1187	317			
C12420	9	2000	SB	McCafferty-Whittle	C	MW1			1279	340			

APPENDIX C

ODOT DRAFT SPECIFICATION

SP745 (DRAFT) *(THIS SECTION REQUIRES SP730.)*

SECTION 00745 - HOT MIXED ASPHALT CONCRETE (HMAC)

(Unless otherwise indicated by instruction, use all the subsections, paragraphs, and sentences on all projects.)

Comply with Section 00745 of the Standard Specifications supplemented and/or modified as follows:

(Use the following subsections 00745.70, .72 .73, and .75 only when pavement smoothness is required by the pavements Design unit.)

[Begin Option Subsections .70, .72, .73, and .75.]

00745.70 Pavement Smoothness - Replace this subsection with the following:

00745.70 Pavement Smoothness - Construct the pavement wearing surface of travel lanes to a profile that does not deviate from longitudinal and transverse smoothness more than the specified limits set forth in 00745.73.

Perform smoothness testing under the supervision of the Engineer with equipment furnished and operated by the Contractor at the Contractor’s expense. Complete all required smoothness testing no later than seven calendar days following final completion of all travel lane paving on the Project. The Contractor accepts the risk that the smoothness may be affected by exposure to traffic between the date the travel lanes are paved and the date the smoothness testing is completed. If the Contractor elects to perform smoothness measurements on a day other than the day the pavement is placed, additional traffic control required for smoothness measurement, and not required for other work, will be at the Contractor's expense.

Add the following subsection:

00745.72 Smoothness Testing Equipment - Furnish all equipment and supplies for determining smoothness.

(a) Straightedge - Provide at least one 12 foot straightedge.

(b) Inertial Profiler - Provide an ODOT certified inertial profiler meeting the requirements of AASHTO MP11-03. The unit must be able to generate International Roughness Index (IRI) for each 0.1 mile segment and also a comparative plot of the raw profile and the profile with a 25 foot moving average filter applied according to ODOT TM 772. The profiler must also be capable of generating electronic files of profile data in ERD format. The profiler shall be calibrated, in good working condition, and ready for operation prior to performing smoothness measurements.

Provide competent and experienced operator(s) for the equipment. The profiler operator shall meet with the Engineer at a mutually agreed upon time prior to beginning smoothness measurements to discuss all aspects of smoothness measurement on the project.

Add the following subsection:

00745.73 Smoothness Testing and Surface Tolerances - Test according to the following.

(a) General - Test the base course with a 12 foot straightedge as directed. Before performing smoothness measurements each shift, verify horizontal and vertical calibration of the profiler according to ODOT TM 772. Provide documentation to the Engineer verifying that the calibrations have been successfully completed. Price adjustment for smoothness will be made according to 00745.96.

(1) Interstate Projects - Test the wearing course with a profiler and provide IRI results and profile traces according to ODOT TM 772.

(2) Non-Interstate Projects – Test the existing pavement prior to beginning paving operations with a profiler and provide IRI results according to ODOT TM 772. Test the wearing course with a profiler and provide IRI results and profile traces according to ODOT TM 772.

(b) Existing Pavement Surface Test – Prior to beginning paving operations on non-interstate projects, run the profiler over traffic lanes for the full length of the Project and 150 feet beyond the Project ends to provide a complete pre-paving profile.

Obtain profiles on the pavement surface in the right-hand wheelpath of the travel lane along a line parallel to centerline. Take the profile on transition areas of entrance and exit ramps, as close to the right hand wheelpath of the through travel lane as practical.

Profiles of the existing pavement shall initially be analyzed by the Contractor according to 00745.73(d), and the IRI results given to the Engineer no later than seven calendar days following final completion of pre-paving smoothness measurements. In addition, submit an electronic copy of all raw profile data files in ERD format for the Project on a floppy disk or cd to the Engineer.

(c) Base Course Surface Test:

(1) Transverse - Test with the 12 foot straightedge perpendicular to the centerline, as directed. The pavement surface shall not vary by more than 1/4 inch.

(2) Longitudinal - Test with the 12 foot straightedge parallel to the centerline, as directed. The pavement surface shall not vary by more than 1/4 inch.

(d) Wearing Course Surface Test:

(1) Transverse - Test with the 12 foot straightedge perpendicular to the centerline, as directed. The pavement surface shall not vary by more than 1/4 inch.

(2) Longitudinal - Run the profiler over traffic lanes for the full length of the Project and 150 feet beyond the Project ends to provide a complete profile.

Obtain profiles on the pavement surface in the right-hand wheelpath of the travel lane along a line parallel to centerline. Take the profile on transition areas of entrance and exit ramps, as close to the right hand wheelpath of the through travel lane as practical.

Profiles shall initially be analyzed by the Contractor according to 00745.73(d), and the profiles and results given to the Engineer no later than eight calendar days following final completion of all travel lane paving on the Project. In addition, submit an electronic copy of all raw profile data files in ERD format for the Project on a floppy disk or cd to the Engineer.

(3) Transverse Joints - Test with the 12 foot straightedge parallel to the centerline, as directed. The pavement surface shall not vary by more than 1/4 inch. This testing is in addition to the testing of 00745.73(d-2).

(e) Determination of the International Roughness Index(IRI):

(1) General - Determine the IRI in 0.1 mile segments and partial segments. Segments shall begin 10 feet into the Project and run consecutively in either the direction of travel or the direction of HMAC placement, as determined by the Engineer. A segment will end as a partial segment and a new segment will begin when the segment sequence is interrupted by stage construction or by profiled areas excluded from the smoothness requirements.

The following profiled areas of pavement are excluded from smoothness requirements:

- Profiles extending beyond the Project ends
- Bridge decks and bridge panels
- First and last 10 feet at the Project ends and bridge end panels
- Ramps and auxiliary lanes
- Shoulders
- Utility appurtenances adjusted by others
- Continuous portions of travel lanes with less than 0.05 mile between excluded areas

The Contractor shall locate excluded areas prior to smoothness measurement. Excluded areas shall be clearly identified on all profiles. Areas excluded from longitudinal profile measurement shall meet the straightedge requirements of Section 00745.73(c-2).

(2) Method of Analysis - Determine the IRI and individual deviations of the raw profile from the 25 foot moving average profile exceeding 0.2 inch by analyzing the profile charts according to ODOT TM 772 and provide the profile charts and results to the Engineer for review. Individual deviation determinations are not required for pre-paving measurements.

Partial segments less than 0.05 mile in length shall be combined with the immediately preceding full segment for IRI determination. Partial segments 0.05 mile in length or greater shall be analyzed separately.

(d) Utility Appurtenances - If the Contractor is required to construct or adjust utility appurtenances, such as manhole covers and valve boxes, the tolerances stated in 00745.73(c-3) apply.

00745.75 Correction of Pavement Roughness - Replace this subsection with the following:

00745.75 Correction of Pavement Roughness - Should testing described in 00745.73 show the pavement does not conform to the prescribed limits of individual deviation, the following shall apply:

(a) General - The Contractor is responsible for locating areas that require corrective work.

(b) Base Course - If the requirements of 00745.73(b) are not met, correct according to one of the following and retest.

(1) Cold Plane Removal - Profile with equipment meeting the requirements of Section 00620.20 to a maximum depth of 0.4 inch.

(2) Grinder - Profile with abrasive grinder(s), equipped with a cutting head comprised of multiple diamond blades to a maximum depth of 0.4 inch.

(c) Wearing Course - After the Contractor has located and staked all individual deviations exceeding 0.2 inch, the Engineer and the Contractor shall meet at a mutually agreed upon time and drive the Project together. Each deviation will be evaluated during the drive-through to determine if corrective work will be required. Disagreements will be resolved by the Engineer.

Correct all individual deviations identified for corrective work during the drive-through, any transverse joint that exceeds the requirements of 00745.73(c-3), and any by one of the methods listed below to the specified limits.

(1) Remove and Replace - Remove and replace the wearing surface lift.

(2) Grind - Profile with abrasive grinder(s) equipped with a cutting head comprised of multiple diamond blades to a maximum depth of 0.3 inch and apply an emulsion fog seal as directed.

The Engineer will drive across each location requiring corrective work to verify that the deviation has been corrected. The Contractor may retest according to 00745.73 the entire length of all segments requiring corrective work, under the observation of the Engineer. Perform all corrective work and profiling at the Contractor's expense, including traffic control.

(d) Time Limit - Complete correction of all surface roughness within 14 calendar days following notification, unless otherwise directed.

[End Option Subsections .70, .72, .73, and .75]

(Use the following subsection .96 when pavement smoothness is required by the pavement design unit.)

[Begin Option Subsection .96]

Add the following subsection:

00745.96 Smoothness Price Adjustment - No separate or additional payment will be made for smoothness testing, as it will be paid for as part of the work under this Section.

(a) General - A price adjustment for smoothness based on the results of the International Roughness Index (IRI) will be made for each 0.1 mile segment or partial segment of HMAC requiring IRI measurement according to 00745.73. The price adjustment made will be applied to all wearing course material placed in the travel lane(s) subject to IRI measurement

(Fill in the blanks with the appropriate pay item names.)

The price adjustment will be applied to the Contract unit price for the Pay item(s) "____________________" and "______________________" for the quantity of material described above according to the following:

INTERSTATE

IRI (inch/mile)	**Contract Unit Price Adjustment**
45.0 or Less	+ 5.0%
45.1 to 54.9	+ 0.5 x (55.0 - IRI)%
55.0 to 70.0	None
70.1 to 99.9	0.833 x (70.0 - IRI)%
100.0 or more	- 25.0%

NON-INTERSTATE

Percent Improvement	**Contract Unit Price Adjustment**
49.0 or more	+ 5.0%
40.1 to 48.9	+ 5.0% - [0.556 x (49.0-PI)]%
23.0 to 40.0	None
13.0 to 22.9	-2.500 x (23.0 - PI)%
0.0 to 12.9	-25.0%
Less than 0.0	Remove and Replace

00745.96(b) will apply when corrective action is taken by the Contractor and the corrected areas are remeasured according to 00745.75.

(b) Adjustments for Sections Requiring Corrective Work - Segments or partial segments corrected and retested according to 00745.75(c) will be subject to the price adjustments described in 00745.96(a) except that no price adjustment will be due to the Contractor for any retested sections with an IRI less than 55.0 in/mile or a percent improvement exceeding 40.0. Segments or partial segments where one or more individual deviations are selected for corrective work according to 00745.75(c) will not be eligible for positive price adjustment. Segments or partial segments where no individual deviations are selected for corrective work according to 00745.75(c) will be eligible for positive or negative price adjustment.

[End Option Subsection .96]