FINAL REPORT

MEASURING, ACHIEVING, AND PROMOTING SMOOTHNESS OF VIRGINIA'S ASPHALT OVERLAYS

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ABSTRACT

This study was initiated with the goal of identifying the predominant factors affecting the achievable smoothness of asphalt overlays. In addition, it chronicles the evolution of Virginia's innovative special provision for smoothness, which was developed specifically for maintenance-type resurfacing. It further provides a critical assessment of the non-traditional equipment and methods as used to administer this smoothness special provision. Finally, it includes a rational economic justification for the continued and expanded use of the pilot specification.

Among the notable findings relating to achievable ride quality are the identified associations with functional classification, original surface roughness, and the use of the smoothness special provision. Issues that were not found to relate significantly to achieved smoothness include surface mix type, the use of additional structural layers, the use of milling, and time-of-day restrictions on construction activities (i.e., night paving).

The dramatic increase in correlation between original and final surface ride quality when milling of the original surface was performed was another interesting finding, as were the additional costs and corresponding additional benefits associated with the use of the special provision.

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INTRODUCTION

Impetus for a New Smoothness Special Provision for Virginia

In early 1995, the Virginia Department of Transportation (VDOT) began to develop the bid package for a rehabilitation project involving nearly 10 km (6 mi) and eight lanes of badly deteriorated interstate highway just southeast of the city of Richmond (the I-295 project). The existing continuously reinforced concrete pavement was to receive a new multiple-layered hot-mix asphalt concrete (HMAC) surface. This project was to be completed with minimum disruption to traffic and was to be constructed within the guidelines of a special provision for ride quality (as directed by VDOT's Chief Engineer).

In 1995, VDOT's only method for regulating smoothness was through a specification that applied an instrument known as the California-type profilograph.[1] The profilograph can be described as a long (7.5 m) rigid frame assembly with several wheels at each end and a measurement wheel at the center. As the instrument moves along a surface, the center wheel travels up and down with variations in the surface. The amount of up and down movement is accumulated and reported as roughness. In some situations, a vehicle can tow the profilograph. More commonly, however, the instrument is propelled manually by an inspector.

The engineers in VDOT's Richmond District had very good reasons for being reluctant to use the existing smoothness special provision. The first of those reasons was that applying the specification to the entire project would involve manual operation of the profilograph for two passes over each of the eight lanes of the project, a total of nearly 155 km (96 mi) of profiling, if all went perfectly. A nearly universal trend toward fewer state-force inspectors would have made it difficult to find and devote the necessary staff to what would have been a formidable task.

A second and perhaps more compelling reason for their aversion to the traditional specification was one of safety. According to statistics published by the Federal Highway Administration's Work Zone Safety Program, more than 700 people, nationally, are killed in work-zone-related accidents each year. In 1995 and 1996, 12 and 11 people, respectively, were killed in Virginia's work zones. Within just a few months leading up to the I-295 project, two Richmond District employees were killed while performing maintenance under traffic. Understandably, there was not a district in VDOT that was more sensitive to the safety of its employees. The fact that the existing Virginia special provision for smoothness involved performing manual tests within several feet of interstate-speed traffic made it very unattractive, indeed.

Virginia's solution was a new specification, one with which testing could be conducted at highway speeds and without the need to expose workers directly to traffic. It was based on the International Roughness Index (IRI) and administered using a laser-equipped South Dakota-style inertial road profiler (SDRP). The format of the specification closely resembled that of the profilograph special provision. The original IRI targets were established using professional judgment combined with an informal study of typical values for new Virginia pavements.

Although highly publicized efforts (such as the I-295 project) are important, they represent only a fraction of the HMAC pavement placed during a typical construction season. In Virginia, the annual maintenance resurfacing program is responsible for a much larger portion of new pavement surface. Every year, VDOT's maintenance resurfacing program involves 2 million metric tons of HMAC covering almost 6,000 lane-km (3,600 lane-mi). The real potential for a smoothness special provision of the type proposed would be realized only through its application to this program. With this in mind, the 1996 resurfacing schedule was amended to include an application of the experimental smoothness specification to 81 lane-km (41 mi) of new surface. In 1997, the pilot was expanded to 611 lane-km (380 mi) in six of Virginia's nine construction districts.

Evolution of the Pilot Specification for Smoothness

1996 Construction Season

The language in the Virginia specification has been revised slightly in each of its 3 years of existence. As discussed, it is modeled after the traditional profilograph specification. The poignant differences are the use of a high-speed inertial road profiler and the IRI to administer it. Technically speaking, Virginia generally reports the average for two wheelpaths of IRI values, or the Mean Roughness Index (MRI).[2] At each 160-m (0.1-mi) interval, an average MRI is generated and an adjustment applied to the unit bid price for the material. In the specification's original form, the adjustments were made in accordance with Table 1.

MRI averages are also calculated and reported at 16-m (0.01-mi) subintervals. These smaller intervals are used to discourage localized roughness or bumps. In the original form, the special provision limited the maximum 16-m (0.01-mi) MRI to 1900 mm/km (120 in/mi). Subintervals with MRI values exceeding this limit were subject to correction and the 160-m (0.1-mi) interval in which the violating subinterval was contained was not eligible for an incentive, regardless of the interval's overall average.

Table 1. Pay Adjustment Schedule for 1996 Construction Season

IRI After Completion (mm/km)	Pay Adjustment (% pavement unit price)
Under 950.0	106
950.1–1025.0	104
1025.1–1105.0	102
1105.1–1260.0	100
1260.1–1340.0	98
1340.1–1420.0	95
1420.1–1500.0	90
1500.1–1580.0	85
Over 1580.1	Subject to corrective action

IRI units may be converted to in/mi by multiplying by 0.06336.

The original pilot special provision also followed the lead of the profilograph specification when allowing exemptions. Specifically, those sections that included the beginning and end joints and those including and adjacent to bridges were not subject to the special provision.

1997 Construction Season

By the end of the first season of the pilot, it had become clear that achieved smoothness varied with functional classification. With this study's preliminary findings as a basis,[3] a collective effort was made to implement modified targets for the approaching construction season. Unfortunately, to implement a specification change for an upcoming season, the changes have to be essentially completed by the end of the previous season. In this instance, that would not have left enough time to review the outcome of the first season and propose major modifications.

There was opportunity, however, to make a couple of minor changes in the special provision between the first and second season. The maximum incentives and disincentives were softened (reduced) and the pay steps were broadened slightly. The target smoothness range necessary to achieve 100 percent payment remained unchanged, but the maximum MRI eligible for payment was increased to 1700 mm/km (110 in/mi). Perhaps the most significant of the changes was acknowledgment of the influence of original surface ride quality. For all practical purposes, the added language requires that a before-overlay roughness survey be conducted. It specifies that a project is not eligible for an incentive if the final surface is rougher after completion of the work, regardless of the average achieved ride quality. Further, if a contractor is able to effect at least a 25 percent improvement (over the original surface) in ride quality, he or she will not be subject to a disincentive, regardless of the degree of roughness remaining in the final surface.

1998 Construction Season

By late summer, 1997, the specification revisions governing the 1998 construction season were complete. The 1998 version provides separate pay adjustment tables for interstate and primary system projects. Table 2 lists the new special provision's stepped pay factors and accompanying required smoothness values for projects on the interstate and primary systems. According to the new pay schedule, contractors working within the special provision on an interstate highway are required to reduce the pavement roughness by an additional 160 mm/km (10 in/mi) with the new surface. The targets for primary system overlays remain unchanged. The updated pay adjustments are consistent with those available on the interstate system, with the appropriate increase in allowable roughness.

Table 2. Pay Adjustment Schedule for 1998 Construction Season

IRI After Completion (mm/km)	Pay Adjustment (% pavement unit price)
Interstate System	
Under 710.0	104
710.1–790.0	103
790.1–870.0	102
870.1–950.0	101
950.1–1100.0	100
1100.1–1260.0	98
1260.1–420.0	95
1420.1–1580.0	90
Over 1580.1	Subject to corrective action
Primary System	
Under 870.0	104
870.1–950.0	103
950.1–1025.0	102
1025.1–1100.0	101
1100.1–1260.0	100
1260.1–1420.0	98
1420.1–1580.0	95
1580.1–1740.0	90
Over 1740.1	Subject to corrective action

IRI units may be converted to in/mi by multiplying by 0.06336.

Copies of the complete specification are available through VDOT's Materials or Construction Division. Changes that have already been discussed for future revisions include continued fine-tuning of targets and a reduction in the number and length of exempt sections.

Benefit of Initially Smooth Pavements

The National Cooperative Highway Research Program (NCHRP) recently published the results of NCHRP Project 1-31, *Smoothness Specifications for Pavements*, by Smith et al.[4] Among the original objectives of that study was an evaluation of the impact of initial smoothness on the long-term serviceability of pavements. The results demonstrated that initially smooth pavements remain smoother over the life of the pavement. The study further showed that at least a 9 percent increase in life could be expected from a 25 percent increase in initial smoothness.

The NCHRP study also evaluated the effect of specifications designed to encourage contractors to construct smoother pavements. A life cycle cost analysis showed that even higher smoothness levels (more stringent targets) than are commonly imposed could be justified by the economic payoff. Likewise, much greater incentives and more punitive disincentives may be warranted. Finally, the NCHRP study demonstrated that if user costs are considered, it is nearly impossible to spend more money on constructing smooth pavements than can be justified, economically.

Issues to Resolve

Virginia's adoption of high-speed inertial profilers and the IRI to control pavement smoothness represents a significant departure from tradition. It is important that the evolution of the new special provision carefully consider the interaction between this somewhat non-traditional approach and typical highway contracting and construction. Established smoothness targets must be achievable yet appropriately challenging. Further, when VDOT engineers develop a schedule for resurfacing, they should understand how the variables they control affect achievable ride quality. They should also appreciate the additional costs and benefits associated with application of special provisions for smoothness.

PURPOSE AND SCOPE

Although this study was initiated with the primary goal of identifying the factors that affect the ride quality of HMAC overlays, it ultimately served three functions. The first was an investigation of the variables that affect achievable smoothness. The second was a critical assessment of the non-traditional equipment and methods as used to administer a special provision for smoothness. The third was a rational justification for the continued and expanded use of the specification.

The study of factors affecting ride quality was limited primarily to variables that were subject to control by the contracting agency (VDOT, in this instance). Examples are the thickness and type of overlay material, the use of milling, the application of additional structural layers, and time-of-day restrictions on construction activities. Additional variables that were examined included performing contractor, original surface ride, predominant original surface distresses, functional classification, and age.

The assessment of the new equipment and methods examined characteristics of sections that are typically exempt from smoothness special provisions. It also critiqued the special provision's ability (or inability) to identify and address intra-project construction variability.

Last, it looked at some of the known peculiarities of the equipment and examined how they might affect its ability to administer a smoothness special provision.

Through an analysis of the additional benefits and costs attributable to the application of the pilot special provision, an economic justification for its use was developed.

METHODS

Analysis of the Factors Affecting Ride Quality

Database Development

An extensive database was developed in support of this study. The foundation of the database was 4,270 lane-km (2,650 lane-mi) of HMAC paving, encompassing two full construction seasons and the entire state. The primary sources for data were the maintenance overlay schedule from the 1996 and 1997 construction seasons, before and after ride quality reports corresponding to the projects on these schedules, the Highway Traffic Records Information System (HTRIS), the annual pavement distress survey, and miscellaneous plant/producer and mix type tables.

Overlay Schedules/Project Description. The data collection methods pertaining to the overlay schedules were described previously by the researcher.[3] To review, the yearly Maintenance Overlay Schedules (Bid Proposal and Contract for Maintenance Resurfacing) were used to establish the population of projects available for survey. By the use of details from the schedule, particular projects were excluded on the basis of length, traffic characteristics, road classification, and/or restrictions on speed.

By the end of the 1997 construction season, 485 projects had been tested for ride quality. Table 3 shows the number of projects per district and their average widths and lengths. Statewide, the projects surveyed ranged in length from just over 0.2 km to nearly 17 km. The average width was just less than 8 m (26 ft, approximately two lanes).

Table 3. Description of Projects

Construction District	No. Sites	Average Width (m)	Average Length (km)
Bristol	40	8.3	4.4
Salem	40	8.2	5.3
Lynchburg	60	7.6	4.9
Richmond	58	8.8	3.3
Suffolk	71	7.6	3.9
Fredericksburg	73	7.7	4.3
Culpeper	96	7.7	4.1
Staunton	37	8.1	5.9
NOVA	10	8.9	3.1

Roughness Equipment and Reporting. Testing was conducted using an International Cybernetics Corporation (ICC) inertial road profiler. The types of tests conducted can be generally categorized as either before-overlay or acceptance. As soon as the approaching season's overlay schedules were released, before-overlay tests were conducted on as many of the to-be-overlaid projects as possible. These tests involved a single pass over each lane of the project. Before-overlay roughness reports consisted of a single project-long average for each lane. Acceptance tests were performed as shortly after completion of an overlay as possible. These tests involved a minimum of two repeat runs for each lane of a project. From these two runs, two summary reports were generated using the ICC reporting software. Using the data from the smoothest run, two additional reports were produced. The first report provided average roughness indices at the intervals used by the specification to administer pay adjustments. The second report supplied these average indices at smaller intervals and was used in accordance with the special provision to assess the need for localized corrections.

Original Pavement Age and Type. The Pavement Subsystem of HTRIS was used to estimate the age and type of the original pavement. An unavoidable consequence of Virginia's maintenance resurfacing practices is an underlying layering that is rarely completely homogeneous. That is, new maintenance overlays often conceal portions of multiple underlying maintenance sections. Clinically speaking, the way to address these situations would be to subdivide the final surface, and corresponding new pavement section, into subsections with homogeneous underlying surface types and ages. In practical terms, however, this would have required a tremendous amount of additional work with little, if any, anticipated benefit. Instead, these discontinuities were generally dealt with through cautious approximations. When determining the age of the original surface, the researcher used a weighted average original surface placement date to represent the approximate age of the underlying surface. When determining the pavement type, the type representing the majority of the underlying surface was selected.

Original Pavement Condition. Information on the condition of the original pavement was taken from VDOT's annual network distress survey. It provides information on the various forms of cracking present in the original surface, as well as the number and severity of patches and potholes. Although the distress surveys also contained independent appraisals of roughness, the MRI values used to represent the "true" original surface ride quality were collected with VDOT's team of ICC road profilers.

Traffic Loading. To be consistent with pavement design practices, traffic loading conditions are represented in terms of 80kN (18 kip) equivalent single-axle loading (ESALs). Unfortunately, although VDOT has now resumed collecting traffic classification data, the information necessary to generate ESALs was not available at this writing. As a surrogate, data were extrapolated from traffic volumes published in 1990, the last previous year of classification data.[5]

Analysis

Sample Stratification. A considerable portion of the data reduction effort was devoted to the grouping of project families. Generally, the objective was to separate and observe trends in the outcome (as measured by ride quality) associated with a series of projects with certain similarities. Obvious families include functional classification and geographically similar project groups. Other families included subcategories of original surface ride quality, projects with and without time-of-day restrictions, paving with and without milling, surfaces with additional structural layers, surfaces over common predominant distresses, and surfaces placed with and without the benefit of the pilot smoothness specification.

Statistical Differences. As often as possible, the analysis attempted to parse the data into two sets of smoothness values with a single dissimilar factor. For example, to determine whether paving at night affected achievable smoothness on interstate highways, the analysis evaluated two sets of roughness indices from interstate paving projects. The first set would include all interstate paving conducted in daylight hours, and the second would be limited to work done at night. F tests were conducted to compare the variances of the respective data sets. Then, the appropriate t tests were run to determine whether a statistically significant difference existed. A significance level of $p < 0.05$ (95 percent confidence level) was used for these analyses.

Correlation Analysis. The more comprehensive databank of original surface characteristics was approached with a more general correlation analysis. This involved comparing final surface ride (the dependent variable) with those continuous to semi-continuous (explanatory) variables associated with the original surface. The product of the analysis was a half-matrix of correlation coefficients that provided the perceived relationship between every variable in the database. To review, a perfect correlation would return a coefficient of 1 (or ↗1), and a complete absence of correlation would return a coefficient of 0. Cheremisinoff[6] provided a guideline for determining whether a relationship actually exists between two variables. For this particular analysis, which included 117 samples, Cheremisinoff indicated that a correlation coefficient of 0.256 is sufficient to suggest with 99 percent confidence that a real statistical relationship exists.

Performing Contractors. The assessment of contractors took a less scientific approach. The simplest element of the contractor evaluation involved looking at their respective average achieved smoothness in each of the three functional classifications. The anticipated relationship between original surface and final surface ride quality made it difficult to base the entire assessment simply on a contractor’s average achieved final surface ride quality. To balance the influence of the underlying surface, the contractor’s ability to improve ride quality (over that measured on the underlying surface) was also included as an indicator of competence.

Payment Simulations. Part of the data reduction involved creating simulated payment schedules. More specifically, to examine how well the pilot smoothness special provision “fit” Virginia’s overlay population, every tested overlay placed during the 1996 and 1997 construction seasons was subjected to a simulated application of the specification. This involved calculating the percent payment that would have theoretically been due a contractor for every interval of pavement surveyed, regardless of whether a special provision for smoothness was applied. This simulation included exemptions for joints and bridges. The average percent paid was reported and stored as a final output.

Assessment of Pilot Smoothness Special Provision

The assessment of the performance of the special provision involved three issues: the allowance for exemptions, the construction variability within projects, and the interaction between the equipment and typical project conditions.

Exempt Sections

As discussed, every project contains intervals that are exempt from the general requirements of the specification. This analysis was designed to determine how much additional roughness (if any) is present in most exempt locations and over what length it is distributed. To examine the additional roughness, the average achieved MRI values were generated for each of the exempt 160-m intervals. Those values were then compared to project-long averages. The affected lengths were established using the 16-m subinterval reports. From these reports, the analyst identified the first subinterval, traveling away from a particular feature, in which the MRI dropped to a value that was consistent with that of the overall project.

Intra-Project Variability

Intra-project construction variability was investigated by comparing theoretical pay adjustments to the number of potential corrective needs for a project. Pay adjustments were taken from the payment simulations performed earlier. The corrective needs were identified by reviewing the 16-m (0.01-mi) MRI reports from each project. The number of intervals exceeding the original 1900-mm/km (120 in/mi) limit was counted, and the numbers were summed. The total divided by the length of the project was used to determine the number of corrections required per kilometer.

Equipment Issues

Observations and tests relevant to equipment performance involved the speed at which tests are conducted, requirements for pre-test section profile, and the influence of the pre-test section profile on the test section smoothness.

Testing Speed. Minimum testing speeds were examined using an exercise that demonstrates the degradation of roughness data as speeds are reduced. In the example, a secondary road outside Charlottesville, Virginia, was selected to conduct repeat roughness tests at different speeds. The first five tests were conducted at 80 km/h (50 mph). The second five tests were run at approximately 50 km/h (30 mph), and the third series of five runs was made at 16 km/h (10 mph). The roughness indices for a single 30-m test section were then calculated and compared for each series.

Pre-test Section Profile. The discussion of pre-test section profile does not follow from a specific series of field tests. Instead, the theoretical equations of motion are drawn upon to offer insight into one of the important limitations of modern profiling equipment.

Influence of Pre-test Section Profile. An experience from a related study demonstrates how preceding pavements can influence the measured roughness of a test section. In this related effort, artificial bumps were temporarily placed on the roadway to allow an analyst to identify the exact location of a 150-m test section. These bumps were approximately 12 mm (1/2 in) thick and roughly 460 mm by 460 mm (18 in) square. They were placed in the center of the right wheelpath at a specified distance preceding and following the test section of interest. One of the artificial bumps was placed exactly 300 mm (1 ft) before the beginning of the test section, and several repeat tests were conducted. Afterward, the bump was removed and several more tests were conducted. In this example, other characteristics of the profile permitted the test section to be identified equally well with and without the presence of the artificial bumps. The ability to overlay profiles from both types of tests (with and without the bump) provided an opportunity to observe the influence of the bumps on the estimated ride quality of the test section.

User Benefit Analysis

The economic justification for the smoothness special provision was based largely on its benefit to highway users. To that end, two approaches were considered.

Rigorous Method

Smith et al.[4] provided a meticulous account of how user costs and initial smoothness can factor into a cost analysis for pavements. In their discussion, they apply cost tables from a 1972 report by McFarland.[7] These tables provide estimates for vehicle operating costs, delay costs, accident costs, and costs due to user discomfort associated with different levels of initial serviceability (primarily ride quality). Using McFarland’s method, the user cost components so profoundly affect the total life cycle costs that traditional agency cost components (i.e., initial construction and maintenance) become irrelevant. Ultimately, the life cycle cost analysis that incorporates these user costs determined that the most cost-effective initial serviceability will be one that exhibits absolutely no roughness, a practical impossibility.

Simplified Method

Whether a rigorous analysis of this sort is reasonable is a source of considerable contention in the transportation community. Given the complexity and anticipated practical arguments against it, this study offers a much simpler approach. This simplified method works with current user fees and willingness-to-pay criteria to arrive at a "reasonable value" for improved smoothness.

One approach to developing a value of highways to the public is to examine current user fees. For example, the average Virginia motorist pays a fuel tax of 9.33 cents per liter (35.5 cents/gal state and federal).[8] If the average automobile consumes a liter of fuel every 10.6 km (25 mi/gal), then the tax per kilometer is approximately 1.42 cents (2.3 cents/mi).

If the objective is a value to the traveling public for an improvement in highway conditions, perhaps the simplest approach is to ask the traveling public what a desired improvement is worth to them. In 1996, a survey[9] commissioned by the National Quality Initiative Steering Committee did exactly that. This survey asked users what they thought of the national highway system and how much they were willing to pay to improve it. The survey determined that pavement conditions were the number one concern of the traveling public. It further determined that these users are willing to pay approximately 1.0 cent per liter (3.5 cents/gal) additional in fuel tax to see pavement conditions improve. Using the same assumed average fuel efficiency (10.6 km/l), the additional tax would equate to approximately 0.09 cents per kilometer.

To sum up, among other fees, the traveling public currently pays approximately 1.42 cents per kilometer in fuel tax. Also, a survey of national users suggested that the highway user is willing to pay an additional 0.09 cents per kilometer for some improvement in highway conditions. Assuming increased smoothness would serve as that improvement, it seems reasonable to value incremental smoothness improvement in terms of tenths of cents per kilometer.

The following offers a method for calculating the total user benefit of an improvement in pavement smoothness. For simplicity's sake, the analysis applies a value of 0.1 cent/km to each 100 mm/km improvement in ride quality. Calculating the total benefit first involves multiplying this 0.1 cent/100 mm/km improvement by the average daily traffic. Next, the length of new overlay and the number of days per year multiply this product. Finally, the total benefit involves multiplying by the expected life of the overlay (approximately 10 years in Virginia). Conservatively, no additional service life is assumed to accompany increased initial smoothness. Since the benefits accrue over time, they are discounted at a nominal rate of 5 percent. To review:

$$\text{Total user benefit} = \$0.001 \times N \times L \times (\text{Users per lane}) \times (P/A, 5\%, 10)$$

where

- User benefit = 0.1 cents (0.001 dollars) per 100 mm/km improvement in smoothness per lane-kilometer
- N = number of 100 mm/km increments of improvement in smoothness
- L = length of overlay

- Users per lane = Average annual daily traffic (ADT) multiplied by 365 days/year and divided by 4 for interstate and divided primary highways and by 2 for two-lane primary highways
- (P/A,5%,10) = equal-payment-series present-worth factor for 10 years service life at 5% = 7.7217.

FINDINGS AND DISCUSSION

Factors and Families Significant to Achievable Smoothness

Distribution of Ride Quality

Figure 1 combines the distributions from the 2 years of roughness testing. It describes a database that contains an average MRI for each lane of every project tested. There are 748 samples of ride quality on original surfaces (scheduled for an overlay). There are 854 samples reporting achieved ride quality of newly placed overlays. In 576 instances, the database contains an average MRI for the original surface and the overlay of the same section of pavement.

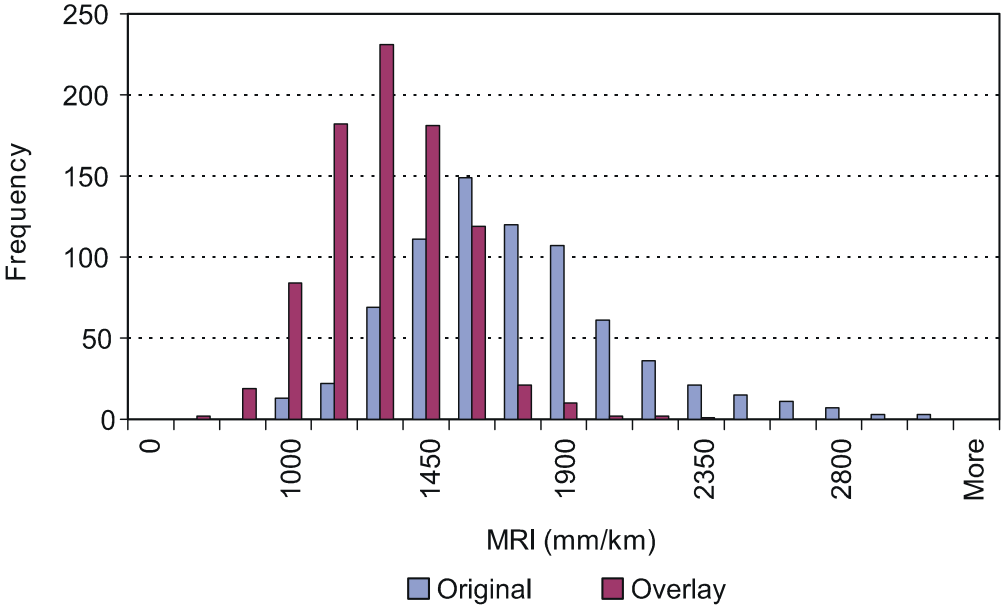

Figure 1. Distribution of Measured Ride Quality

Functional Classification

Roadway functional classification was among the first variables to demonstrate a significant relationship with achieved smoothness. As the data are separated into the respective classifications (Figure 2), it is evident that overlays of the interstate are generally smoother than

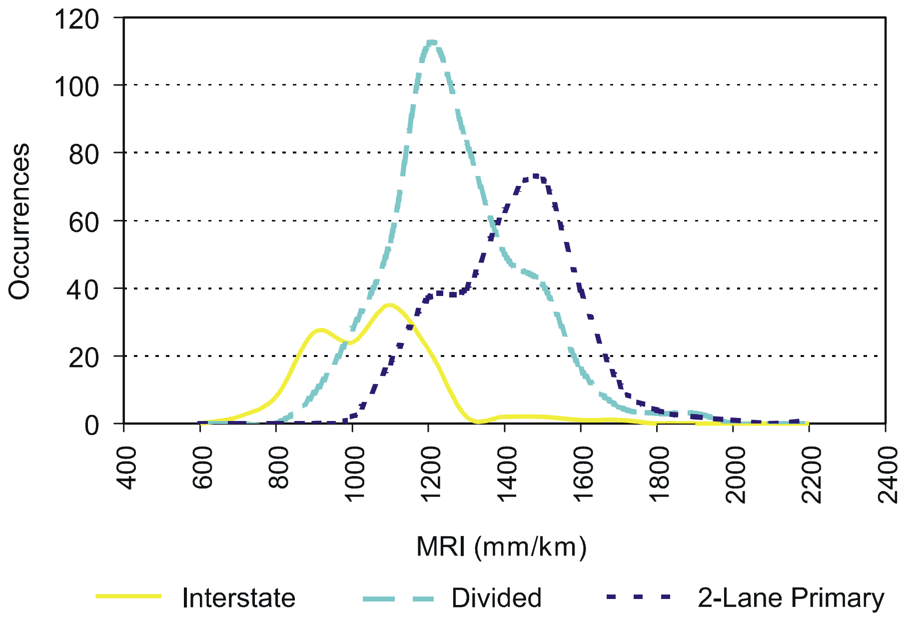

Figure 2. Distribution by Functional Classification

overlays placed on the primary system. Table 4, which provides the statewide averages and standard deviations of smoothness, indicates that interstate paving is also subject to less variation. Apparently, the slight increase in variability on primary highway construction does not change with the further classification of divided versus two lane.

Table 4. Average Achieved MRI

Functional Classification	Average (mm/km)	Standard Deviation (mm/km)
Interstate	1004	160.9
Divided	1224	178.8
Two lane	1372	178.6

MRI units may be converted to in/mi by multiplying by 0.06336.

District

Geographically, the trends are less distinct (see Table 5). The southwestern part of the state (Bristol, Salem) has historically enjoyed some of the smoother pavements, at least on the higher classification roadways. The Northern Virginia District is the most urban district in the state and consequently must contend with a variety of design, construction, and maintenance peculiarities that make it more difficult to concentrate on achieving smooth pavements. Unfortunately, data were not available for interstate paving in the Northern Virginia and Fredericksburg districts.

Table 5. Achieved Smoothness by District (MRI, mm/km)

District	Interstate		Divided Primary		Two-Lane Primary	
	Avg. MRI	Count	Avg. MRI	Count	Avg. MRI	Count
Bristol	941	22	1229	40	1118	18
Salem	977	28	1218	29	1321	24
Lynchburg	*	-	1145	78	1420	40
Richmond	1079	32	1289	37	1346	55
Suffolk	1144	10	1157	95	1349	40
Fredericksburg		-	1284	82	1451	66
Culpeper	1046	16	1220	90	1383	84
Staunton	945	31	1278	8	1315	33
NOVA		-	1515	18	1215	2

*There are no interstate highways in the Lynchburg District.

Performing Contractor

Figures 3 through 5 provide average achieved smoothness and average improvement for those contractors for whom the database includes a minimum of 10 samples per functional classification. Obviously, a combination of a good (low number) rating for final surface ride quality with a large improvement (high number) would suggest a better performing contractor. Contractor 22, for example, used large improvements to provide better-than-average final riding surfaces on interstate and two-lane primary projects. Contractors 9 and 10 were similarly successful on divided primaries.

Some contractors have the luxury of conducting work on fairly smooth original surfaces. In many situations, accepting the fact that many contractors are very regional, these same

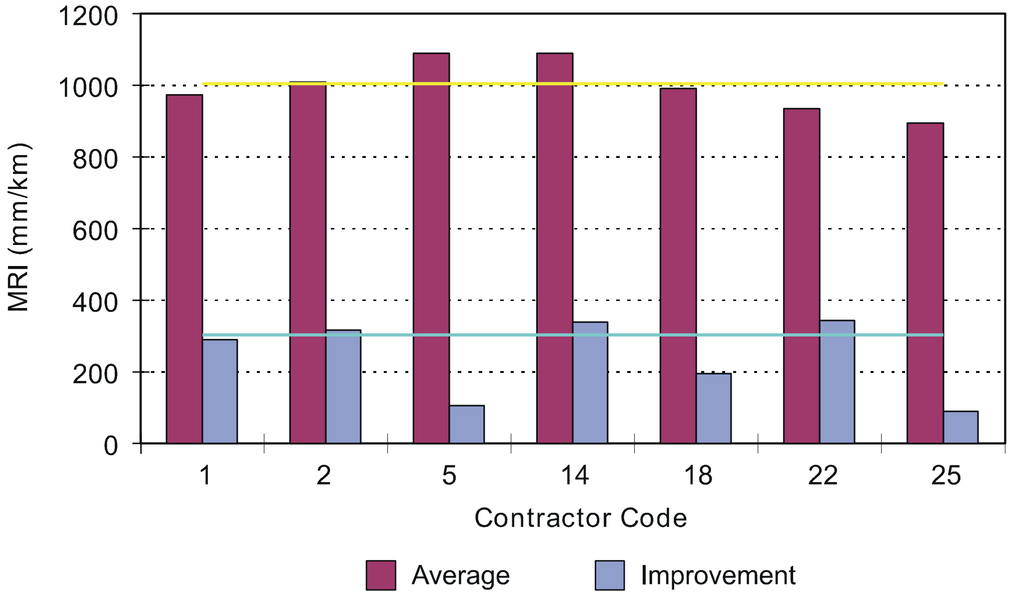

Figure 3. Contractor Performance for Interstate Resurfacing

Figure 4. Contractor Performance for Divided Primary Resurfacing

Figure 5. Contractor Performance for Two-Lane Primary Resurfacing

contractors are somewhat responsible for these smoother working surfaces. In these cases, the performing contractor may not need to effect significant improvements to supply good final riding surfaces. Examples of this include the higher classification roads in the Bristol District. The numbers associated with contractors 15 and 21 on divided primary projects (low average MRI and low improvements) are perhaps examples of this.

Characteristics of Original Pavement

The analysis of the impact of the characteristics describing the original surface began with the construction of one large correlation matrix. Table 6 provides just the portion of the matrix that pertains to achieved final surface ride quality (the appendix contains the complete correlation matrix).

Table 6. Correlation with Overlay MRI

Data Source	**Characteristics of Original Surface**	**Overlay MRI (Correlation Coefficients)**
PaveTech Distress Survey	Allig Low	0.013
	Allig Med	0.096
	Allig High	0.000
	Longit Low	-0.144
	Longit Med	-0.248
	Longit High	0.082
	Transv Low	0.084
	Transv Med	0.096
	Transv High	0.123
	Patch Low	0.195
	Pothole	0.107
	Rough Low	0.358
	Rough Med	0.636
	Rough High	0.463
	Sect PCI	-0.184
HTRIS	YDESAL	-0.484
	Age	-0.083
VDOT Road Roughness Equipment	Original MRI	0.590

Note: Allig–Low, Med, High represent the various degrees of alligator cracking observed. *Longit* represents longitudinal cracking, and *Transv* indicates transverse cracking. *Rough* values are roughness classifications included in the distress survey (also IRI values), and the *Sect PCI* value is a combined condition index used by the pavement management system. The *YDESAL* variable is the approximate yearly ESAL count. *Original MRI* is the MRI of the underlying pavement as measured by VDOT road roughness equipment.

Distresses

If significant relationships exist between the various types of original surface distresses and the achievable smoothness of overlays, this analysis failed to identify them.

Traffic

likely, however, that yearly ESAL counts in this instance are reflecting the previously noted association with functional classification. In fact, a second correlation analysis that observed YDESAL versus functional classification (1, interstate; 2, divided primary; 3, two-lane primary) revealed a high correlation coefficient, *R*, of ↗0.58. These higher classification roads, which are built to handle larger volumes of traffic, are usually made up of more modern, less active geometry, which in turn contributes to smoother pavements.

Age

The original surface ages varied from as young as 1 year to as old as 30. Table 7 provides the average age by functional classification of pavements selected for overlay. Statewide, Virginia asphalt surfaces are exposed just under 10 years before being overlaid or milled and replaced. The age of an underlying surface, by itself, appears to have little if anything to do with the achievable smoothness of an overlay.

Table 7. Age of Overlaid Pavements

Functional Classification	Average Age (yr)
Interstate	10.4
Divided primary	9.6
Two-lane primary	9.8

Ride Quality

Within the discussion on contractor influence, the weight given to the ability to affect ride improvements suggests that the ride quality of the original surface is important. Indeed, the ride quality of the surface underlying a new overlay is widely suspected of having a predominant influence on achievable smoothness. In the correlation analysis just discussed, the population sample was limited to those records for which a variety of other original surface data were available. Nonetheless, it identified a correlation coefficient between original and final surface MRI of 0.59. When the analysis is expanded to all records for which original and final surface MRIs are available, a much larger database is available. Figure 6 illustrates the results of this analysis, which contained 576 pairs of final surface and original surface MRI values. The correlation coefficient of 0.67 suggests a very significant relationship. The fitted equation, however, shows that the original surface MRI is not, by itself, adequate to predict the achievable smoothness of an overlay. The goodness-of-fit statistic (R^2) does suggest that nearly 45 percent of the achievable smoothness can be explained by the original surface roughness. For that reason, original surface MRI was used to categorize the majority of the remaining variables. That is, to prevent original surface roughness from masking the contribution of other variables, many of these variables were viewed through a simple filter on original surface ride quality. Their evaluation was based on how they affect overlay smoothness for pavements with good, fair, or poor original surface ride quality. Table 8 provides the specific numbers that define the limits of each of these categories.

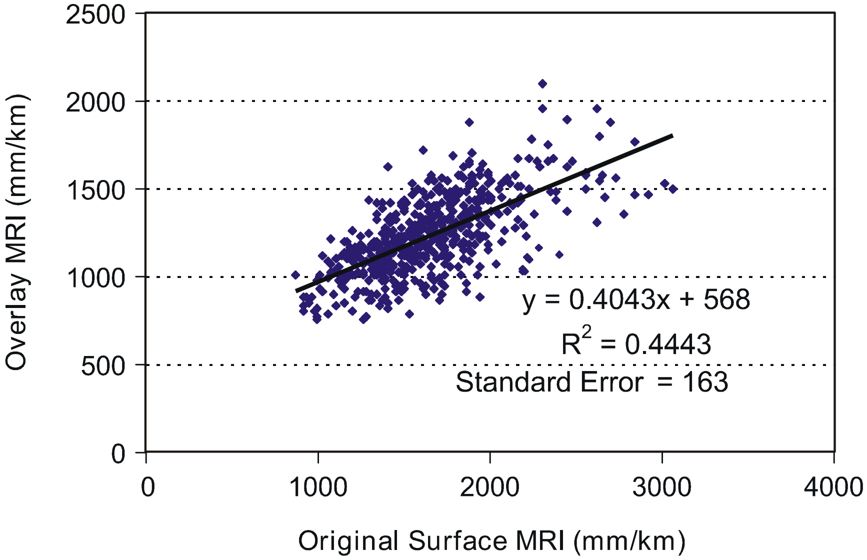

Figure 6. Original Surface vs. Overlay Ride Quality

Table 8. Categories of Original Surface Ride Quality

Original Surface MRI	Smoothness Category
Less than 1400 mm/km	Good
1400 to 1900 mm/km	Fair
Greater than 1900 mm/km	Poor

MRI units may be converted to in/mi by multiplying by 0.06336.

Characteristics of New Surface

Mix Type

Several district pavement experts have noted instances in which the use of a particular pavement surface type (e.g., SMA, SM-1A) appeared to be a factor in the achieved average ride quality. To investigate whether this is a more general trend, this study included an evaluation of the overlay ride quality as related to pavement type. The database includes ride quality samples from eight surface mixes used in Virginia over the 2-year period of this study. Unfortunately, some mixes are used so sparingly that it is difficult to gather a significant representative sample. For the benefit of this exercise, the effect of mix type was considered for only those mixes for which at least 10 samples were available. Figure 7 represents the average achieved ride quality for those most prominent pavement types used in Virginia. All of the predominant surface mixes included in the analysis use the same aggregate gradation. The five letter designations (A–E) represent differences in the stiffness and amount of binder contained in the mix. For the five mixes, there are as few as 14 samples and as many as 235 samples representing each.

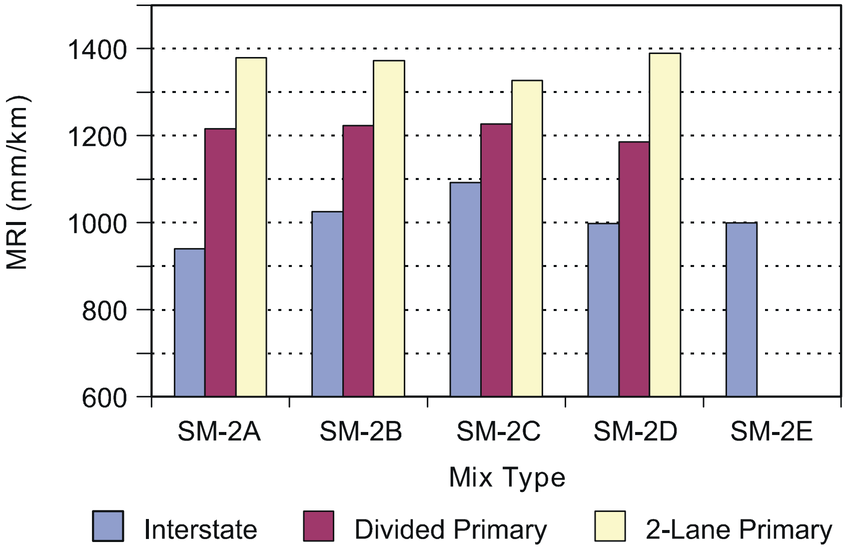

Figure 7. Influence of Mix Type

The only statistically significant difference associated with mix type was that between the ride quality of the SM-2A and SM-2C mixes placed on the interstate. These mixes are unique in that they are designed to contain less asphalt cement. Consequently, their workability may be reduced slightly. However, if this is a trend, it does not carry over to the other classification roadways. Generally speaking, among the most commonly used mixes, type does not appear to be a significant factor affecting achievable smoothness.

Thickness

Intuitively, the more material (thickness-wise) that a contractor is allowed to use, the better his or her chance of achieving a smooth riding surface. Theoretically, a variable such as thickness can vary continuously. In actual practice, there are a fairly limited number of application rates selected for surface mixes. Table 9 provides the number of sections tested per prescribed overlay thickness. By a considerable amount, the 38-mm (1½-in) lift is the most common thickness used for maintenance resurfacing. The second most common thickness is 42 mm (just under 1¾ in). The only other thickness represented on more than 10 test sections was 40 and 51 mm (1 9/16 and 2 in, respectively). Figure 8 illustrates the average ride quality, categorized by original surface smoothness, for each predominant thickness. Although more samples of the thicker surfaces would lead to more statistically reliable conclusions, the thicker overlays were usually smoother. The more commonly prescribed thickness amounts all appear to be associated with similar achievable smoothness. The tendency for the thicker overlays to mitigate the influence of the underlying surface is encouraging (the achieved smoothness is similar, regardless of original surface ride quality).

Table 9. Tested Overlay Thickness

Thickness (mm)	Tested Sections	% of Total
35 (150 lb/y^2,1$^3/_8$ in)	2	0.2
38 (165 lb/y^2,1½ in)	639	77.0
40 (175 lb/y^2,1$^9/_{16}$ in)	18	2.2
42 (180 lb/y^2,1$^5/_8$ in)	136	16.4
43 (185 lb/y^2,1$^{11}/_{16}$ in)	6	0.7
46 (200 lb/y^2,1$^{13}/_{16}$ in)	8	1.0
51 (220 lb/y^2,2 in)	19	2.3
53 (230 lb/y^2,2$^1/_{16}$ in)	2	0.2

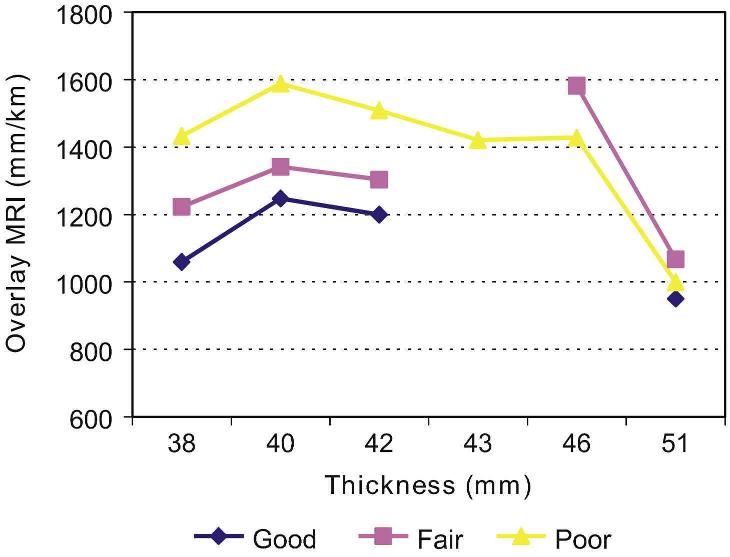

Figure 8. Achieved Smoothness by Overlay Thickness

Special Treatments/Circumstances

The relevance of special treatments or circumstances was derived from information provided on the resurfacing schedule. A special treatment consists of milling and/or the prescription for an additional structural layer. Milling was presumed when the amount of milling/planing called for on the schedule was substantial enough to accommodate general project milling. The additional structural layer was noted when the schedule included an item for base or intermediate-type mix over the same section as was designated for the overlay. Special circumstances were limited to any time-of-day restrictions that were included on the schedule. Specifically, the necessity to perform the work at off-peak hours (e.g., at night) is thought by many to affect the quality adversely and, correspondingly, the achievable smoothness.

Although the testing for this study was extensive, there were not always enough samples of a given combination of treatment, functional classification, and original surface ride quality to warrant drawing any meaningful conclusions. As a rule, no observations were reported for situations in which there were not at least 8 samples. As such, none of the illustrated relationships in the following sections represents anecdotal observations for one or two occasions.

Milling

Milling of the original surface before an overlay is placed rarely appears to affect the achievable smoothness of that overlay positively. Only in the case of interstate paving over good riding original surfaces was there a slight statistical advantage for the milled versus the non-milled work (see Figure 9). In the approximately 40 surveyed instances where overlays were placed over poor riding divided primary surfaces, the 9 cases in which milling was prescribed appeared to be worse.

Figure 9. Influence of Milling on Achievable Smoothness

Base/intermediate Mix

Much like the philosophy discussed in the analysis of overlay thickness, one would expect contractors to be able to achieve smoother final surfaces if given an opportunity to place an additional layer between the original surface and the overlay. However, the findings illustrated by Figure 10 suggest very little in the way of a relationship. In fact, none of the differences was found to be statistically significant.

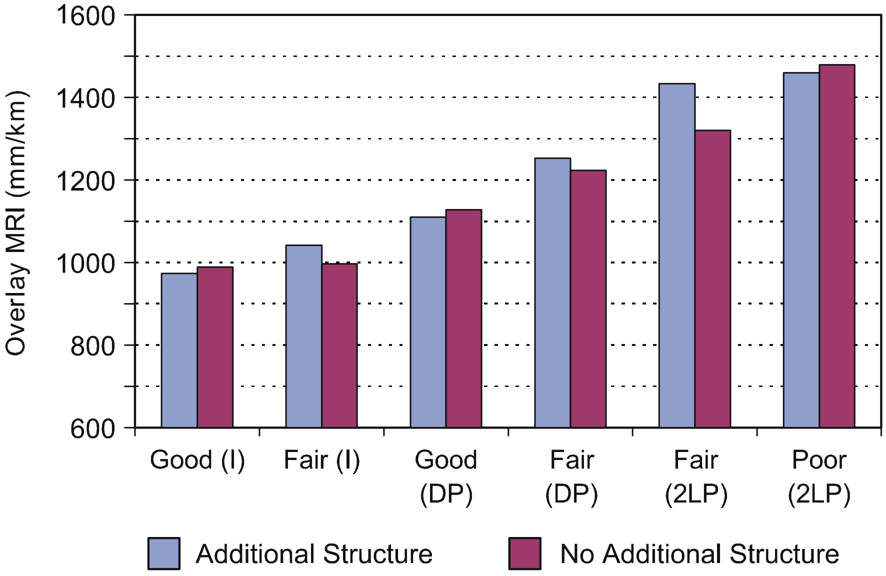

Figure 10. Influence of Additional Structure on Achievable Smoothness

Combined Milling and Additional Structure

In terms of potential for improving ride quality, it seems reasonable to anticipate that the best combination would involve milling, an additional structural layer, and a new surface. In this case, the contractor has three opportunities to address underlying, or existing, ride quality issues. To evaluate to what extent this combination affects achievable smoothness, Figure 11 compares the achieved improvement in ride quality accomplished on the three functional classifications. It illustrates how milling combined with additional structure compares to simple mill and replace.

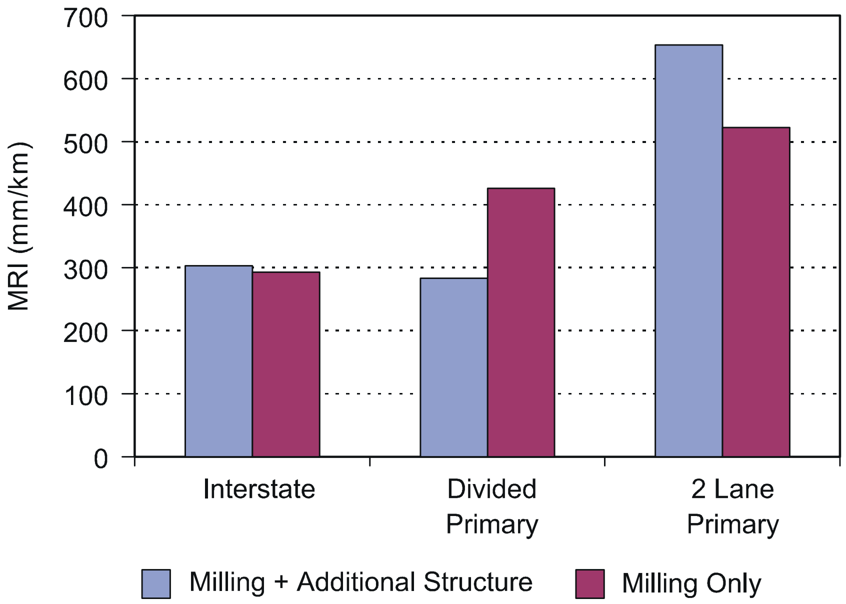

Figure 11. Ride Quality Improvement with and Without Combined Milling and Additional Structural Layer

On the interstate system, the difference is minimal. On divided primaries, larger average improvements occurred with mill and replace. On two-lane primaries, the milling combined with additional structure provided the largest improvements. Although there were at least 45 samples of each of the other five categories, there were only 11 tested instances on two-lane primaries where milling and an additional structural layer were used together. Only that difference on divided primary highways proved to be statistically significant. The practical significance, considering the amount of variability, is less impressive.

The model of final surface smoothness solely as a function of original surface ride quality (conducted earlier) produced a goodness-of-fit statistic (R^2) of 0.44. It seems reasonable to assert that the act of removing some portion of the original surface through milling before placing an overlay would have some affect on this relationship. Further, one would guess that milling would weaken this relationship. Likewise, when an additional structural layer is inserted between the final and the original surface, it also appears reasonable to expect the relationship to deteriorate. In either case, the predicted consequence might be desirable, particularly if the original surface is exceptionally rough.

To investigate whether these expected effects actually occur, independent regression analyses were conducted on six subsets of the database. Table 10 reports the goodness-of-fit statistics for each model of predicted overlay smoothness as a function of original surface smoothness. The *Milling* and *No Milling* models essentially divide the database in two, as do the *Add. Str.* and *No Add. Str.* models. The *Mill & Replace* and *Mill & Add. Str.* models are further refinements of the model for *Milling*.

Table 10. Influence of Milling and Additional Structural Layers on Correlation Between Original and Achievable Smoothness

Practice	Goodness of Fit, R^2
N/A (all records)	0.44
Milling	0.53
No Milling	0.34
Add. Str.	0.48
No Add. Str.	0.43
Mill Only	0.55
Mill & Add. Str.	0.50

Oddly, those practices that would seem to degrade the relationship between original and final surface smoothness actually improve it. In every category where the original surface was milled or an additional structural layer was prescribed, the model of final surface smoothness as a function of original surface smoothness demonstrated a better fit. Perhaps the most conspicuous trend is the significant increase in correlation whenever milling is an issue. In cases where mill and replace *(Mill Only)* is used as a resurfacing strategy, an additional 11 percent of the variability can be explained.

Time-of-day Restrictions (Night paving)

As expected, time-of-day restrictions were generally associated with functional classification and geographic location. An overlay in the Northern Virginia or Richmond District on the interstate system is nearly always placed at night. Two-lane primary work in the Staunton District, on the other hand, can almost always be done during daylight hours. For the 101 tested sections where the paving was conducted at night, the statewide average achieved smoothness was 1068 mm/km (68 in/mi). Of the remaining 729 sections where the paving was conducted during the daytime, the average smoothness was nearly 200 mm/km rougher. Figure 12, which includes categorization by function classification and original surface smoothness, demonstrates that night paving is at the very least inconsequential. Again, the only case where the difference was found to be statistically significant was for divided primary overlays placed over fair riding original surfaces. In this instance, the work conducted at night was approximately 160 mm/km smoother than that done in daylight. Unfortunately, the 11 observations comprising the night-paving-over-good-original-surfaces are hardly enough to warrant sweeping conclusions.

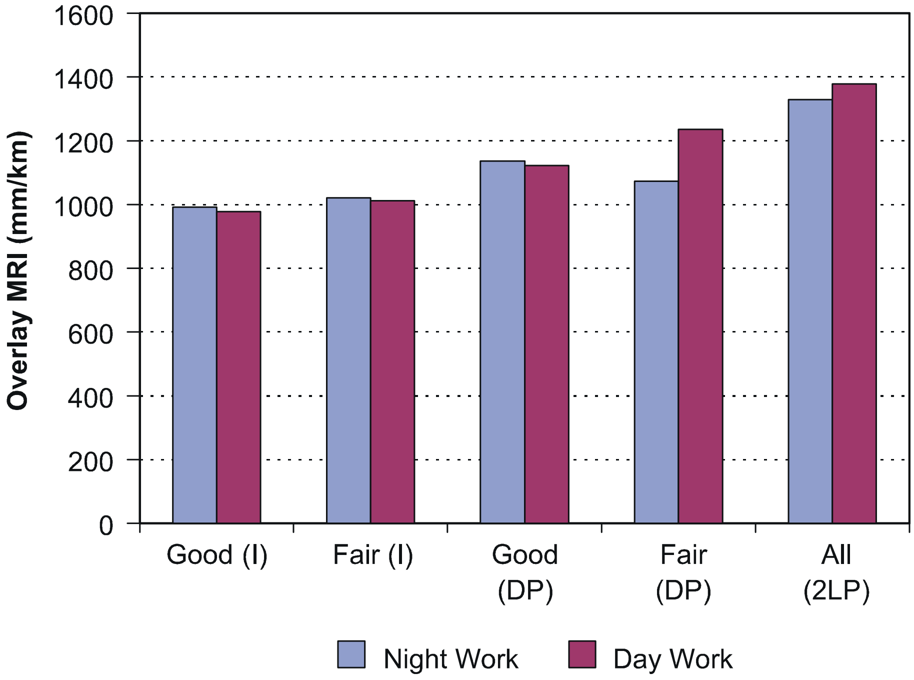

Figure 12. Influence of Time-of-day Restrictions

Application of Special Provision for Smoothness

The piloted specification received fairly broad application, although by direction it was limited to interstate and divided primary projects. It was apparently most effective when it accompanied overlays being placed over good riding original surfaces. For instance, both categories of overlay that were placed over good riding original surfaces measured approximately 100 mm/km smoother when they were placed in accordance with the special provision for

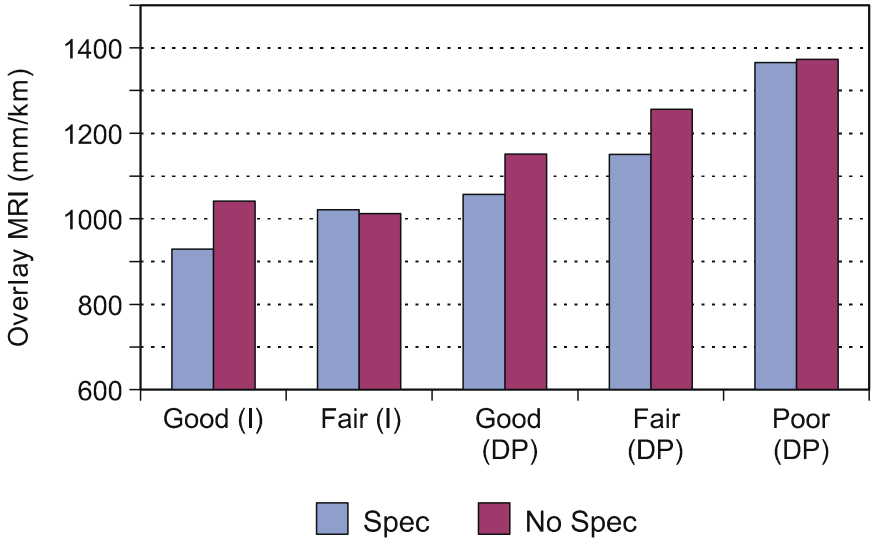

Figure 13. Influence of Smoothness Special Provision

smoothness (see Figure 13). On fair riding divided primary roads, use of the specification was equally effective.

Unit Price of Mix

In an effort to relate construction costs and the achieved smoothness, winning bid prices were obtained for each project. For the two resurfacing schedules that formed the basis of this study (schedules from 1996 and 1997), the average bid price for installed asphalt concrete mix was $27.99 per metric ton ($30.87 per English ton). Table 11 lists the average bid prices and achieved smoothness values for each district. In the Northern Virginia District, where the industry is extremely competitive, the resurfacing work was done at an average price of just over $24 per metric ton. Unfortunately, that relatively inexpensive pavement had the roughest average ride quality. In contrast, the Bristol, Suffolk, and Staunton districts routinely spend the most money (on a per ton basis) resurfacing pavements. However, the higher prices are generally associated with better overall smoothness (lower MRI values).

Table 11. Average District Bid Prices and Overlay Smoothness

District	Bid Price ($/ton)	Overlay MRI (mm/km)
Bristol	30.34	1123
Salem	28.70	1164
Lynchburg	25.54	1234
Richmond	26.76	1257
Suffolk	29.81	1210
Fredericksburg	25.38	1360
Culpeper	24.26	1282
Staunton	29.65	1106
NOVA	24.35	1455

When the data are divided by functional classification, the higher priced work is conducted on the interstate and generally found to be the smoothest. The bid price of plant mix placed on the primary system does not appear to vary dramatically from divided to two-lane, both of which being considerably lower than for the interstate. In Table 12, the average original surface and overlay MRI values are reported for each of the functional classifications, along with the associated average bid price. The last column *(Improvement)* reports the average decrease in MRI, from the original surface to the new overlay, achieved per unit bid price. VDOT receives an average improvement of approximately 10, 15, and 20 mm/km per dollar (bid) on interstate, divided primary, and two-lane primary projects, respectively.

Table 12. Incremental Improvement by Functional Classification (Ignoring Smoothness Special Provision)

Functional Classification	Bid Price ($/ton)	Original MRI (mm/km)	Overlay MRI (mm/km)	Improvement (mm/km per $)
Interstate	30.54	1314	1004	10.1
Divided primary	26.54	1607	1217	14.7
Two-lane primary	26.21	1892	1376	19.7

To address the relationship between agency costs and smoothness, the actual paid price must be considered. When the project is not subject to the specification for smoothness, the price paid is assumed to be equivalent to the bid price. However, when the specification is a factor, the price paid must reflect the possible incentives and disincentives. Table 13 is similar to Table 12 except that it distinguishes between the interstate and divided primary projects for which the smoothness special provision was and was not an issue.

Table 13. Incremental Improvement by Functional Classification

Functional Classification	Paid Price ($/ton)	Original MRI (mm/km)	Overlay MRI (mm/km)	Improvement (mm/km per $)
Interstate (w/spec)	34.3	1321	965	10.4
Interstate (w/o spec)	27.72	1294	1048	8.87
Divided primary (w/spec)	30.00	1617	1173	14.8
Divided primary (w/o spec)	25.69	1602	1232	14.4

Clearly, overlays that were not placed in accordance with the specification were considerably more expensive to construct. However, in spite of the additional unit cost, the improvement in ride quality per dollar was higher. The 1996 and 1997 versions of the smoothness specification incorporated only one set of target values. That is, regardless of functional classification, contractors were subject to the same payment adjustments for a given level of achieved smoothness. Since that time, separate target values have been implemented for interstate and primary system projects. If this same analysis were conducted using the more modern targets, the “paid price” for interstate paving would reflect lower incentives.

The sampling performed to assemble this database was designed to incorporate road types that would eventually be candidates to come under a special provision for smoothness. As a parting look at the relationship between price and ride quality, every section in the database was subjected to a simulated application of the special provision. To that end, theoretical payment adjustments were applied to every project, regardless of functional classification. Table 14 reports the simulated unit prices generated from that exercise. As compared to the average original bid prices (Table 12), a network-wide application of the specification would have resulted in a slight increase in average price paid for interstate paving. There would be a corresponding slight decrease in the price paid for divided primary work and a 70 cent decrease in the unit price paid for work on two-lane primary roads. The overall effect is remarkably slight.

Table 14. Simulated Unit Prices Assuming Blanket Application of Smoothness Special Provision

Functional Classification	Simulated Price paid ($/ton)	Overlay MRI (mm/km)
Interstate	31.30	1004
Divided primary	26.40	1217
Two-lane primary	25.51	1376

Assessment of the Pilot Special Provision

The process of data compilation and the extensive fieldwork required to conduct this study permitted a unique assessment of the pilot special provision. The following sections present findings related to special situations and concerns involving the semantics of the specification and the equipment used to administer it.

Exempt Sections

Ride Quality. Figure 14 provides the exempt intervals' average smoothness for each functional classification. When compared to the overall achieved smoothness, the traveling public can expect to encounter approximately 70 percent more roughness at the first joint, 45 percent at the last joint, and about 46 percent at either end of bridges. The ride quality of these intervals tends to vary less with functional classification than has been observed for most mainline paving. As a consequence, the relative roughness at these exempt sections appears higher on higher classification roadways. For example, the roughness encountered at the first joint on an interstate overlay is approximately 90 percent higher than on the remainder of the overlay. The same section on a two-lane primary is only about 60 percent rougher.

Length-to-Equilibrium. When considering roughness of exempt sections, two types are of concern. The first is produced as the contractor attempts to gain control over ride quality at the beginning of the project or just after a bridge. The second results as the pavement mat is tapered off at closing joints along the project (e.g., bridges) or at the end. Figure 15 summarizes the lengths necessary to address the respective features in each of the three functional classifications. Although the length of overlay affected by the first and last joints are very similar, the length affected by the beginning joint was nearly universally longer than that at the end. The reported length of affected overlay at bridge approaches includes the total from before and after the structure. For the entire state, contractors usually gain control of a surface within

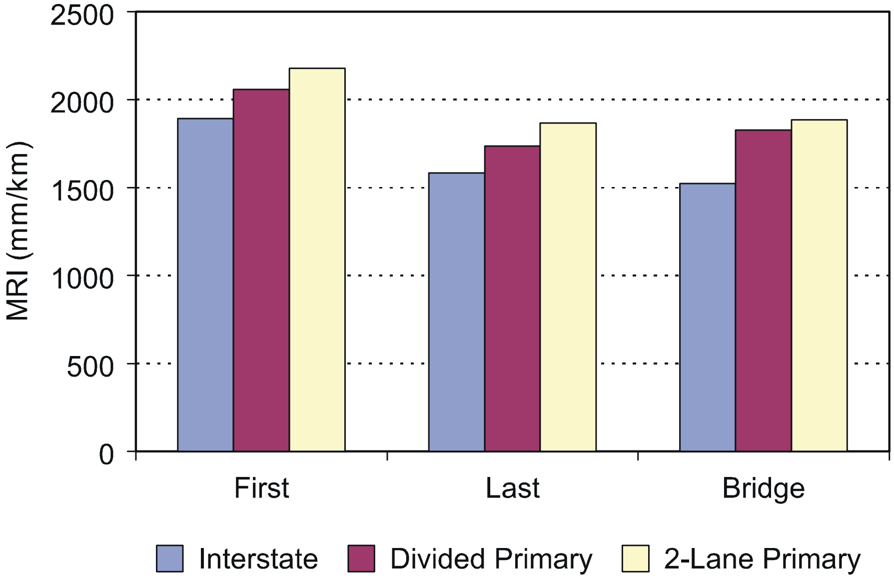

Figure 14. Average Ride Quality of Exempt Sections. *First* represents the very first tested portion of pavement at the beginning of the project. *Last* is the corresponding last tested interval of the project. *Bridge* represents the combination of smoothness values of any sections adjacent to bridges.

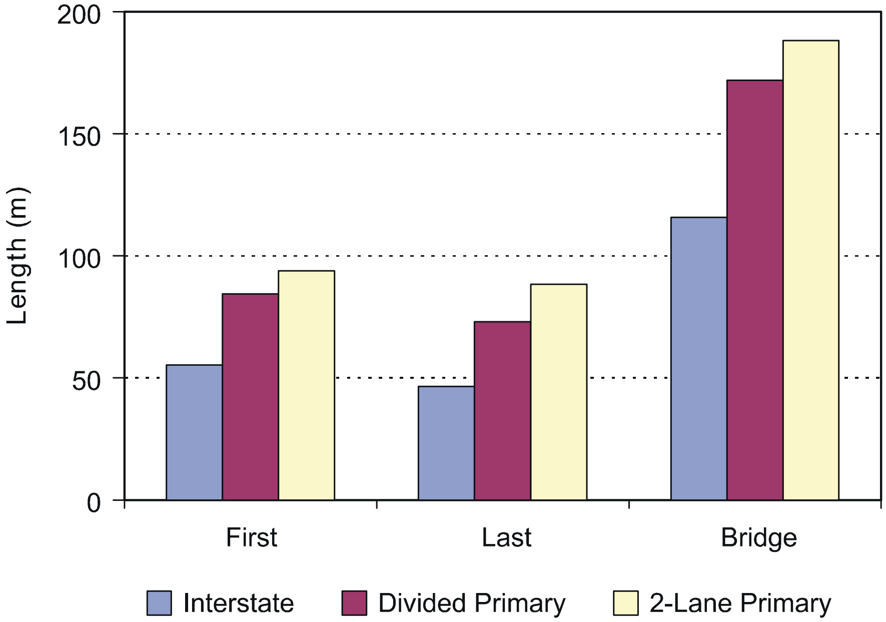

Figure 15. Average Length to Equilibrium

84 m of the beginning of an overlay. In at least 32 cases (of 426) in the 1997 construction season, however, the contractor had established control over ride quality within the first 16-m (0.01-mi) subinterval.

Intra-Project Variability

Many overlays placed on Virginia's highways are associated with good average smoothness values, even though they otherwise appear quite ordinary to marginal in quality. Part of this inconsistency may be attributable to roughness of a wavelength that is perceptible to the traveler but not measured by the high-speed profiler or significant to the IRI algorithm. More often, however, the traveler's perception is because the variability of smoothness is greater than desired. In these cases, the current average-based specification tends to mask possible fluctuation in ride quality. In spite of the use of the short-interval reports, which are generated specifically to identify locally rough spots, the current averaging approach can effectively bridge significant surface events.

To illustrate, Figure 16, which plots the number of possible corrections per kilometer of paving versus the theoretical average percent paid (for the 1997 data only), clearly shows the strong and desirable correlation between potential corrections and potential payment. However, it also demonstrates that smoothness conforming to and exceeding the requirements of the current special provision can still contain frequent local roughness in excess of the limit at which corrections could be necessary. In fact, for those projects that would have been eligible for 100 percent payment or better (as per the specification) there was an average of just over one potential correction per kilometer. In the worst case, a pavement that would have fallen just short of achieving the maximum bonus also would have been subject to nearly three potential corrections per kilometer.

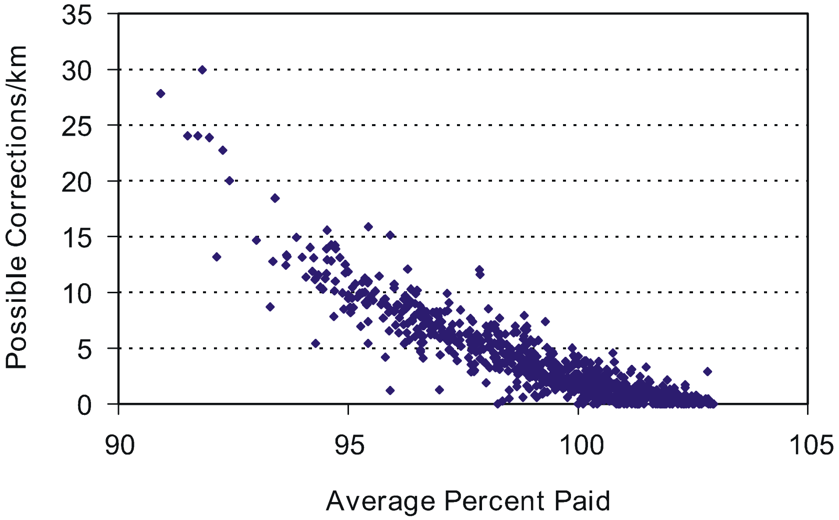

Figure 16. Possible Corrections Versus Average Percent Unit Price Paid

Variability Specification. The researcher and his colleague Hughes suggested one approach to dealing with high levels of variability in overlay ride quality[10] by proposing a special provision that combined achieved average IRI with the standard deviation of IRI to assess the ride quality of a project. The specification uses the percent within limits (PWL) concept and involves a quality level analysis. Acceptable and rejectable quality levels were estimated using rideability data from the 1996 population of overlays. Separate levels of quality were proposed for interstate and divided primary projects. Evaluating the ride quality of a given payment lot involves defining its distribution and comparing it the established quality level for its functional classification. The distribution is defined using the lot's average MRI combined with the standard deviation, as calculated from the 10 sub-lots. The distribution establishes the percent of the lot that falls within specification limits, or the PWL. Using this PWL, a linear pay factor equation can be used to establish the appropriate pay adjustment.

Roughness Profiles. Presently, the practice of quality level analysis is inconsistent with Virginia's specification philosophies. A possible alternative for dealing with intra-project variability may involve a concept known as a roughness profile.[11] A roughness profile, as distinguished from a simple elevation profile, consists of a profile produced from a series of roughness (e.g., IRI) values. These roughness numbers are generated from and centered on a moving base-length of longitudinal profile. For example, in a roughness profile that uses the IRI, the IRI value for 50 m of a pavement profile would be generated at each running meter, combining 25 m of the profile preceding this location with 25 m from beyond.

This is best explained with an illustration. Figure 17 shows roughness profiles for slightly over 150 m (505 ft) of a single wheelpath of pavement. The plot contains roughness profiles for two base-lengths, as well as an overall average. As indicated, the first series represents a base-length of 10 m, and the second series is for a base-length of 100 m. The overall average IRI for this section is 1460 mm/km (93 in/mi). As the base-length of the roughness profile is increased, the reported IRI values remain closer to the overall average throughout the length of the project. Roughness fluctuates dramatically when the base-length is much shorter.

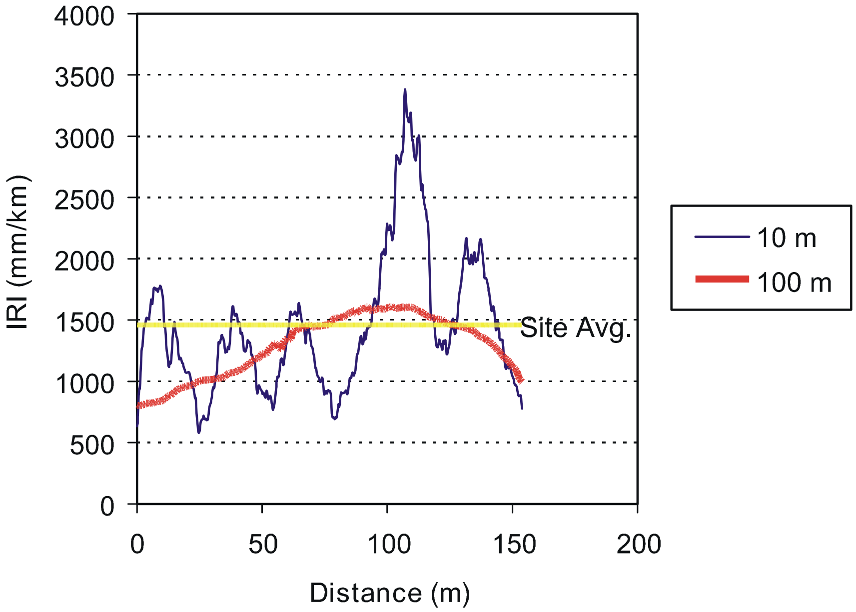

Figure 17. Roughness Profiles for Varying Base-lengths

Factors Involving Equipment That Affect Measured Ride Quality

Minimum Test Speeds. Several important peculiarities of high-speed inertial profiling systems tend to make them less practical for assessing smoothness on some highway surfaces. In general, their limitations center on their need for speed. At the nucleus of inertial road profilers are accelerometers. The function of the accelerometer is to help establish an inertial reference plane. The distance from this reference plane to the pavement surface is measured using height sensors (in VDOT's case, laser range finders). The longitudinal distance is then supplied from an electronic distance transducer. The information from all three types of sensors are synchronized and combined to generate a profile.

Of course, a good profile begins with a good reference plane. A good reference plane can be achieved only with accurate accelerometer data, and good accelerometer data are difficult to get without adequate accelerations. Finally, a key to meaningful accelerations is the right kind of motion, which in the case of inertial profilers requires moving along a highway surface at a specified minimum rate of speed.

Figure 18 summarizes three sets of tests, each conducted at a different speed, that describe a single 30-m (100-ft) test section. Without a baseline profile, judging the relative accuracy of the three test sets is difficult. It is safe to say, however, that the 80 and 50 km/h tests produce similar average values with very comparable amounts of variability. The 16 km/h tests, on the other hand, appear to produce much higher estimates of roughness with a notable loss of precision. In general, Virginia's experience has been that a minimum speed of 30 to 40 km/h (20 to 25 mph) is sufficient to ensure reliable profile data.

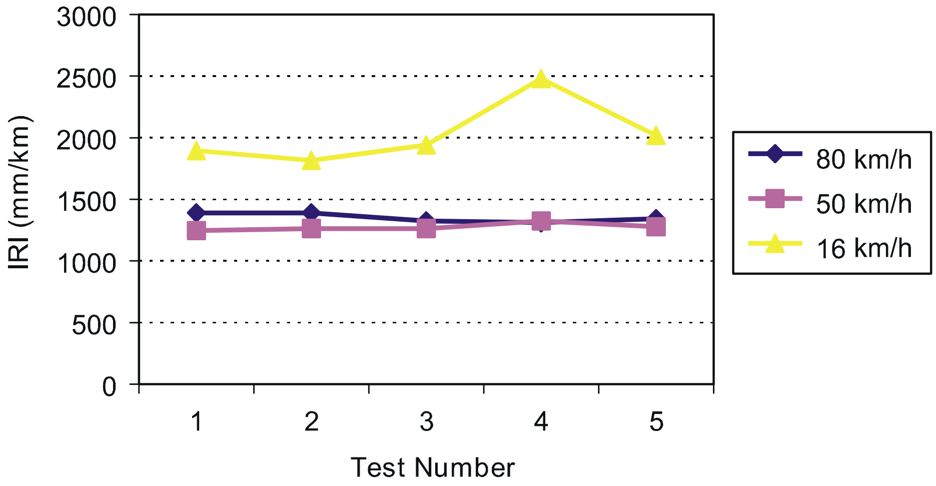

Figure 18. Effect of Speed on Measured Roughness

Minimum Length of Pre-test Section Profile. Another idiosyncrasy of high-speed inertial profilers involves their need for space. Once again, this relates to the inertial nature of the profiler (its reliance on accelerometers). Through use of the fundamental mathematical relationships of motion, it can be shown that the derivative of an equation describing position will yield a value or an equation for velocity. Further, the first derivative of velocity yields the acceleration. It is this principle that permits a reference plane (continuous series of positions) to be generated from acceleration data. Actually, it is this principle in reverse. That is, positions are generated by twice integrating the accelerations. Unfortunately, natural products of integration are constants, which can be difficult to determine. For most practical problems, these constants can be determined or approximated by knowing initial conditions. With inertial profiling, these initial conditions are approximated by engaging the profiling system and running some nominal distance while the system stabilizes. For VDOT's high-speed equipment, the fabricator suggests at least 100 m (300 ft) of waste profile before the beginning of the specific section to be profiled.

Influence of Preceding Profile. The underlying or original surface ride quality has a significant influence over the achievable smoothness of a final surface. This might be considered the *vertical* influence pavements exert on other pavements. To a much more limited extent, there is also a *longitudinal* influence affecting the ride quality of a given surface. More specifically, the ride quality of a highway surface is not independent of the riding surface just before it. This is the case regardless of whether that surface is a stretch of roadway pavement or a bridge deck. Of course, with a true profile, an analyst should be able to remove the specific portion of pavement of interest and generate a roughness index (IRI) that incorporates no influence from anything at either end of it. In reality, however, this is not what happens. Examples of surface features that provoke more than instantaneous reactions from vehicles and their occupants are potholes, debris, deteriorated joints, and rough bridge approaches.

Figure 19 includes profiles of the first 30 m of a test section. Series 1 and 2 are typical profiles generated while an artificial bump is located 0.3 m immediately before the section.

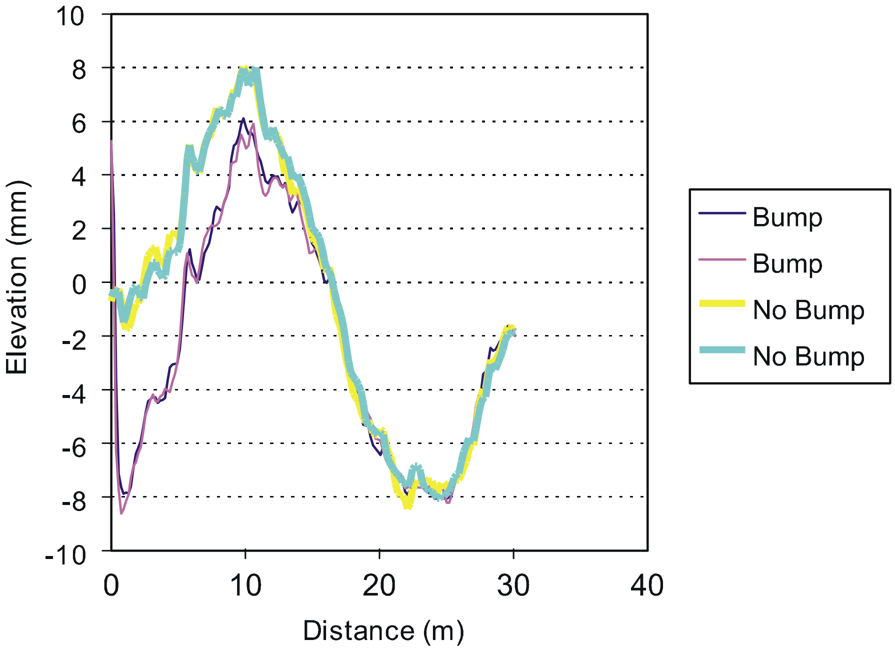

Figure 19. Profile Reaction to Artificial Bump

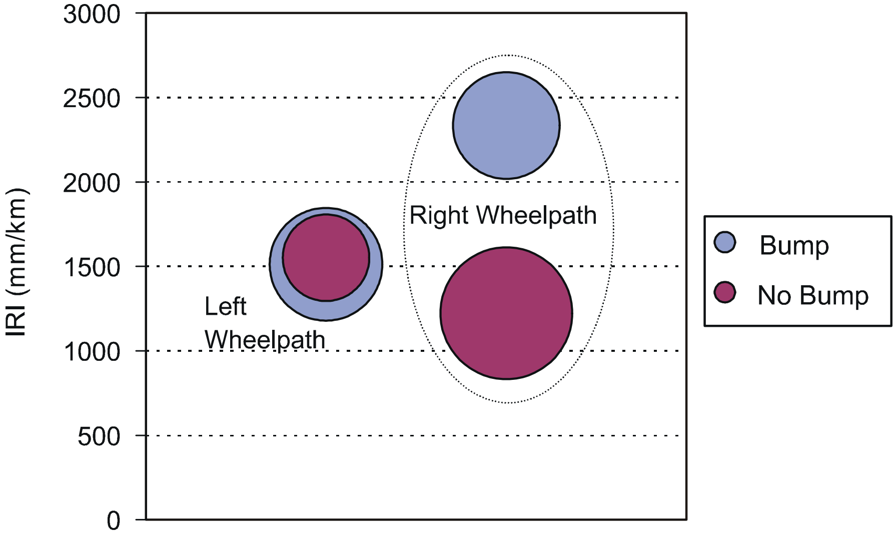

Figure 20. Additional Roughness Attributable to Artificial Bump

Series 3 and 4 represent the same 30-m section without the bump. The beginning of the profiles collected without the bump has a distinctly different shape from those collected with the bump. The centers of the bubbles in Figure 20 represent the average left and right IRI values generated from five repeat tests conducted with the bump installed and five more with the bump removed. The sizes of the bubbles indicate the range in the five repeat runs. Recalling that the bump was installed only in the right wheelpath, it is relevant to note that although the second series of tests show a marked reduction in right wheelpath roughness without the bump, there has been no apparent change in the left wheelpath (where no bump was ever introduced). This exercise demonstrates that a nominal perturbation (12 mm in thickness) 0.3 m before a section can result in more than 1000 mm/km of additional roughness being reported for a subsequent 30-m section.

Incidentally, because of this phenomenon, the use of the artificial bumps was modified. In all subsequent tests involving them, the artificial bumps were relocated approximately 8 m back from the beginning of the test sections. For all practical purposes, this appears to eliminate the effect.

User Benefit of Smoothness

The total benefit of increased smoothness has two primary ingredients: increased service life and lowered user costs. Smith et al.[4] discussed the expected increase in service life attributable to some unit of improvement in initial smoothness. It seems appropriate to examine the benefit of smoothness to the traveling public.

The simplified approach discussed earlier (see Methods) was applied to the data available from this study to conduct a user benefit versus construction cost analysis. Tables 15 and 16 summarize the results. For agency construction costs, the researcher estimated that the resurfacing program applies an average of 320 metric tons of surface mix per lane-kilometer. As

Table 15. User Benefit from Improved Ride Quality

Specification Applied?	Functional Classification	Length (km)	Annual User Benefit ($/km)	Total Lifetime Benefit ($)
Yes	Interstate	334	11,260	29,055,529
	Divided primary	413	8,025	25,616,381
No	Interstate	343	5,098	13,496,264
	Divided primary	1581	2,515	30,700,983
	Two-lane primary	1562	1,972	23,783,207

Table 16. Construction/Agency Costs

Specification Applied?	Functional Classification	Average Unit Agency Cost ($/km)	Total Agency Cost ($)
Yes	Interstate	10,954	3,660,308
	Divided primary	9,600	3,968,572
No	Interstate	8,870	3,041,264
	Divided primary	8,221	12,994,491
	Two-lane primary	8,387	13,097,567

expected, the average construction costs for those surfaces subject to the specification were higher than for those that were not. However, there was a dramatic difference in annual user benefit from the respective categories of new surface. The average annual user benefit derived from improved smoothness was $9,471 per kilometer on projects subject to the smoothness special provision. For those projects that did not benefit from the special provision, the annual user benefit was just over $2,500 per kilometer. Although the overlays on two-lane primaries typically achieve some of the largest improvements, the lower relative traffic volumes limit the effective overall user benefit.

Finally, Table 17 provides the most succinct perspective of the effect of the smoothness special provision on the improvement in ride quality. For the two seasons comprising this study, the total additional lifetime user benefit derived from the 740 lane-km subjected to the specification is nearly equivalent to that accomplished on the remaining 3,485 km. The user benefit/agency cost ratios are correspondingly lopsided in favor of using a specification for smoothness.

Table 17. User Benefit Versus Agency Construction Costs

Special Provision Applied?	Total Benefit (10 yr Service Life) ($)	Total Construction Cost ($)	Benefit/Cost Ratio
Yes	54,671,910	7,628,880	7.2
No	67,980,454	29,133,322	2.3

CONCLUSIONS

Factors That Affect Achievable Smoothness

Of the variables evaluated in this study, only three influence, with any practical significance, the achievable smoothness of an overlay: the roadway functional classification, the ride quality of the original (underlying) pavement, and whether the overlay was subject to the provision for smoothness. A fourth variable, the thickness of the new surface, showed some indication of affecting ride quality. Unfortunately, there were too few examples of surfaces exceeding 40 mm of thickness to draw wholesale conclusions.

1. *Functional classification.* Overlays placed on interstate classification highways are generally smoother and subject to less variability than those placed on the primary systems.

2. *Original surface ride quality.* The achievable smoothness of a new surface is strongly associated with the ride quality of the original, underlying surface.

3. *Application of smoothness provision.* The provision for smoothness was found to be most effective when applied to overlays placed over good riding interstate pavement, good riding divided primary pavement, and fair riding divided primary pavement.

Factors That Did Not Affect Achievable Smoothness

For several of the investigated variables, the lack of a measurable influence on ride quality is notable. Those variables that were expected to affect achievable smoothness, but did not, include surface mix type, additional structural layers, milling, and the requirement to perform the work at night.

1. *Surface mix type.* The evaluation of mix type was limited to one family of mixes, the SM-2 series. Within that family, no consistent trends associated with ride quality were identified.

2. *Additional structural layers.* The analysis of the influence of additional layers on final surface smoothness returned no statistically significant results. There was little positive response, in terms of achieved overlay smoothness, associated with an added intermediate or base layer. On the contrary, for two categories of resurfacing, the added structural layer actually resulted in higher average roughness.

3. *Milling.* Milling was more notably associated with a higher average roughness (overlays of poor riding divided primaries). Overall, the results were mixed to inconclusive.

4. *Night paving.* Perhaps the lack of a negative influence associated with paving at night was the most unexpected finding. Statewide, the necessity to pave at night had almost no measurable affect on achieved smoothness. For the one exception, resurfacing of fair riding divided primaries, the analysis suggested an overall improvement when the work was done at night.

Additional Observations

1. *Milling increases the correlation between the smoothness of the original surface and the smoothness of the overlay.* An increase in the correlation between original surface ride quality and achievable overlay smoothness occurred when a schedule project incorporated milling.

2. *Using the smoothness specification is a good investment.* Overlays that were subject to the pilot provision were constructed at higher unit costs than overlays that were not. However, the improvement in ride quality (per dollar) over the original surface was at least equivalent, if not superior, to that realized on the non-specification projects.

3. *User benefits dwarf construction costs when the specification is used.* Benefits measured in construction cost savings pale in comparison to those achieved in additional value to the traveling public. When the specification is used, the additional benefit realized by users may exceed the original construction costs within 14 months of overlay service-life. In contrast, when the specification is not applied, almost four years of service are required to recoup the construction costs.

RECOMMENDATIONS

- *Do not use high-speed profilers in highly urban areas, particularly where projects involve multiple signalized intersections.* In these situations, the profiler operator can have difficulty negotiating the signal lights, not to mention the slower moving, higher volumes of traffic that generally accompanies them.

- *Do not use full-size (and weight) profilers for monitoring new construction, especially for rigid pavements.* Interim testing on partially completed surfaces can be difficult to impossible. Depending on the construction site, it can be very dangerous. By the time an agency can assess the rideability of an ongoing paving operation, it may be too late for a contractor to adjust to correct any problems.

- *Consider eliminating the "ending" exemptions on the smoothness special provision for maintenance.* In fairness to the contractor, the specification should appropriately excuse contractors from responsibility for things he or she cannot control. It is reasonable, for example, to allow an exemption to a contractor for that portion of the overlay just past an exiting bridge approach. On the other hand, a good argument for excluding the last pavement joint from a smoothness tolerance is less obvious. Similarly, removing the exemption from joints leading up to bridge approaches should also be considered. In either case, the contractor is given an opportunity to address ride quality in the surface leading up to that feature.

- *Use "roughness profiles" to address intra-project variability.* An advantage to adopting roughness profiles is that the specification language would remain essentially unchanged. A base-length of 16 m (52.8 ft), which is used by the current bump special provision, is probably suitable. The improvement would be that the effect of bumps, or locally rough spots, would no longer be washed out across two adjacent 16-m intervals. Any major surface flaw 16 m or less in length would eventually manifest itself completely in a single MRI value. In effect, the specification has been tightened significantly with a very minor change in wording, if any.

- *Do not use conventional mill and replace to address smoothness issues.* Regardless of the mechanism, milling appears to fortify the relationship between before and after overlay ride quality. If the original surface is fairly smooth, this may be desirable. If not, then the engineer may wish to investigate using something other than traditional constant-depth milling or mill and replace.

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