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16. Abstract

Smoothness, the absence of bumps and dips in the riding surface of a pavement, improves the quality of the ride and is believed to prolong the life of the pavement. This research addressed the impact of potential pay adjustments for smoothness on maintenance contract prices for hot-mix asphalt. In addition to the construction costs associated with potential incentives/disincentives for smoothness, the research examined the financial value of the resulting product (presumably smoother pavements). The analysis included maintenance cost savings for the owner/agency, as well as any reduction in delay and operating costs for the motoring public.

A detailed statistical analysis of 5 years of Virginia's plant mix resurfacing schedules found no statistically definitive impact on bid price as a result of the Virginia Department of Transportation's (VDOT) special provision for rideability for asphalt pavements. A similar analysis on a more focused data set, however, did document a lifetime reduction in the International Roughness Index (IRI) of almost 9 in/mi. This reduction in roughness (increase in smoothness) implies an increase in pavement service life, which translates into reduced annual maintenance costs. Although the analysis supports as much as 7 years in additional functional life, an example calculation demonstrates that just a 2-year life extension will supply approximately $1,295 (about 6% of material costs) in owner/agency savings for every lane-mile of highway that is resurfaced under the special provision for rideability. If VDOT continues to employ the special provision with the frequency it has averaged over the past 4 years (1,033 lane-miles per year), using the special provision will save on the order of $1.3 million per year.

The lifetime decrease in roughness can lead to even more dramatic user cost savings. One real example provided in the report demonstrates a fuel cost savings (for trucks alone) of $160,000 over a 10-year period for each lane mile of highway that is resurfaced under the special provision for rideability.

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FINAL REPORT

IMPACT OF A SMOOTHNESS INCENTIVE/DISINCENTIVE ON HOT-MIX ASPHALT MAINTENANCE-RESURFACING COSTS

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(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

In Cooperation with the U.S. Department of Transportation
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INTRODUCTION

Smoothness, the absence of bumps and dips in the riding surface of a pavement, improves the quality of the ride and is believed to prolong the life of the pavement. In 1996, the Virginia Department of Transportation (VDOT) implemented the Special Provision for Rideability (McGhee, 1999). Although the special provision was applicable to new construction work, it was specifically developed to cover maintenance-resurfacing projects. Relying on the employment of high-speed inertial profilers, the special provision established targets, as well as incentive/disincentive (I/D) payment ranges, in terms of the International Roughness Index (IRI) (Perera and Kohn, 2004; Sayers, 1995), a metric used to quantify the size and frequency of bumps and dips in a riding surface. Since its debut, the special provision has evolved to establish targets that better reflect the owner/agency expectations for various highway classifications (e.g., interstate and non-interstate). Later versions of the special provision have incorporated shorter pay lots (0.1-mi to 0.01-mi), a "percent improvement" mechanism to accommodate single-lift resurfacing, and higher potential I/Ds to motivate contractors further to focus on smoothness.

The maintenance-resurfacing schedules constitute a significant portion of VDOT's investment each year in hot-mix asphalt (HMA). In two previous construction seasons, 2002 and 2003, the total estimated value of HMA placed through the maintenance-resurfacing program was remarkably consistent at just over $120 million per season. In 2002, VDOT distributed approximately $197,500 in incentive payments for smoothness. For the same time period, VDOT withheld more than $180,500 in disincentives, for a net of approximately $17,000. In 2003, $301,000 of incentive payments was awarded and $94,000 was held back for a net of just over $207,000 in incentives for smoothness (Reid and Clark, 2003).

The increase in net incentives from 2002 to 2003 came in spite of the fact that fewer projects (and 83 fewer lane-miles) were tested as part of the program (Reid and Clark, 2004a). A 5-year trend in final surface IRI for projects subjected to the special provision likewise indicated a slow, but positive move toward smoother construction (see Figure 1).

Although agency officials believe the impact of the special provision to be generally positive, questions continue to come from the industry. Many of these questions relate to the reasonableness and uniformity with which it is administered at the project level. For example, contractors are occasionally faced with situations in which they are asked to achieve a smooth

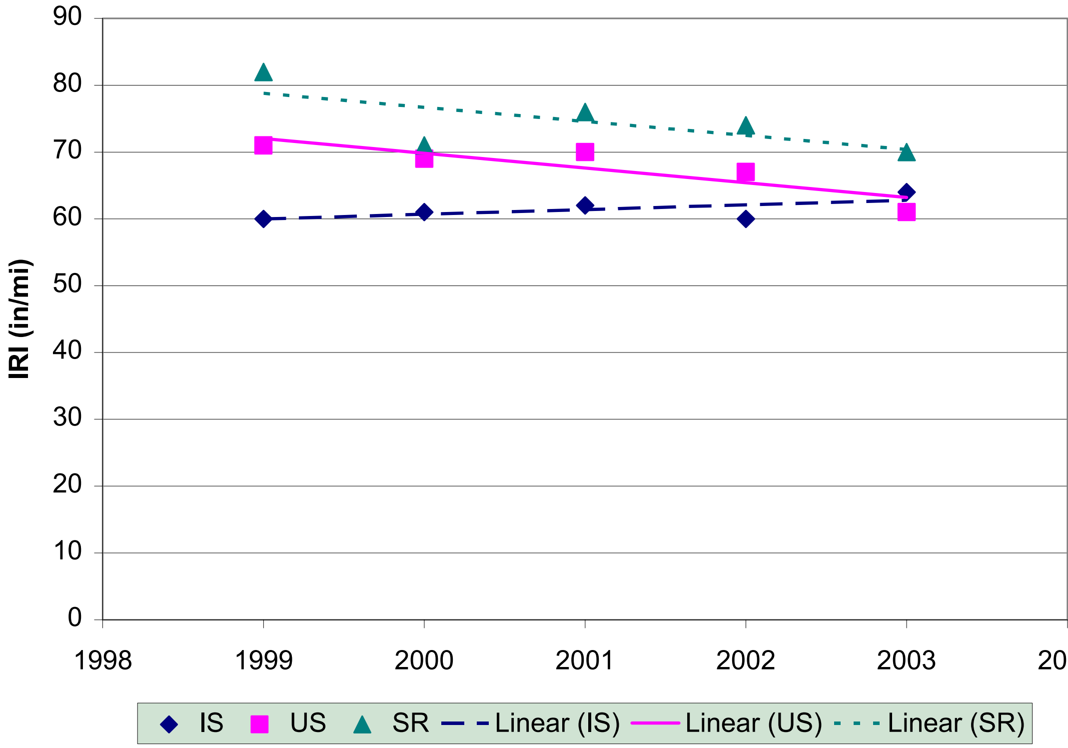

Figure 1. Five-Year Trends in Achieved Smoothness for "Specification Projects." IS = Interstate, US = US Primaries, SR = State Route Primaries. Reflects maintenance resurfacing work only. Adapted with permission from Reid and Clark, 2004b.

riding pavement while also meeting existing curb-and-gutter elevations that are not perfectly aligned and uniform. Another example involves the influence of scabbing (by-product of milling) on achievable smoothness and of not specifying leveling courses when they may improve an existing surface that exhibits a distorted cross-section.

Fortunately, reasonable and competent professionals can resolve nearly all of these differences by partnering on a case-by-case basis. There are, however, more global issues being raised by industry and agency officials alike. These issues pertain to the balance (or lack thereof) of the pay adjustment schedules, the magnitude (dollar-wise) of potential I/Ds, and the actual financial impact of providing for I/Ds (e.g., are contractors "bidding in" I/Ds?).

At the heart of this last series of issues is the dearth of information regarding the actual monetary value of smoothness. From the user's perspective, benefits include vehicle operating and repair costs. From the perspective of third parties who happen to live and work in the neighborhood, the reduction of pollutant emissions is a potential benefit. As pavement roughness affects rolling friction, the pollutant emissions that a change in roughness would affect most are (1) gases and particulates incidental to fuel consumption and (2) tire noise. From the agency/owner's standpoint, the life-cycle cost advantage of smoothness is easy to accept although not necessarily easy to quantify. NCHRP 01-31 (Smith et al., 1997) found that "added pavement life can be obtained by achieving higher levels of initial smoothness," a 25% increase in smoothness (profile index) corresponding to a 9% increase in service life. Conversely, rough pavements provoke more severe dynamic loading from heavy trucks and as a consequence are likely to incur higher lifetime maintenance costs and provide shorter service lives. As elusive as the real value of smoothness may appear, truly defensible I/Ds will not be possible until this value has been quantified.

PURPOSE AND SCOPE

The purpose of this project was to estimate the impact of potential pay adjustments for smoothness on bid prices and the corresponding ultimate costs of HMA maintenance construction. The study addressed the value of the cost savings (attributable to smoothness) to the owner/agency, motorists, and third parties. The project approached these issues through pursuing answers to the following four questions:

1. How have/do potential I/Ds affected bid prices?

2. What is smoothness worth to the owner agency in terms of life-cycle costs?

3. What is smoothness worth to the traveling public?

4. Given the potential value of smoothness to the owner agency and to the traveling public, what I/D schedule is justifiable?

METHODS

Literature Review

Relevant literature was reviewed. The researchers used the TRIS Online database maintained by the Transportation Research Board, the public web search engine Altavista ™, and published and personal lists of references. The literature included publications from major accelerated loading facilities, analysis within pavement management systems that related specifically to network smoothness or roughness issues, and work aimed at developing background/support for various performance-related specifications

Supporting Data

To address the agency costs and benefits associated with smoothness provisions, two bodies of VDOT data were brought together. The first contained a limited sample of IRI measurements for pavements constructed heretofore under a rideability specification and for a control group of comparable pavements constructed without such a specification. The second and more extensive database contained past years' bid prices, with accompanying information on the use (or not) in each contract of the rideability specification and of other contract terms suspected to influence bid price.

Analysis

The analysis phase used the VDOT data to address the following questions:

1. What impact does a potential I/D have on the achieved smoothness?

2. What impact does an I/D have on sustained smoothness (and service life)?

3. What impact does an I/D have on the bid price per ton (or per mile)?

The analytical methodology followed the life-cycle cost principles prescribed by the Federal Highway Administration (FHWA) (FHWA, 2002; Walls and Smith, 1998) and VDOT's Materials Division (2001). It proceeded on the assumption that the benefits of increased smoothness, if achieved, would show up as cost savings in two areas: (1) savings in road user costs that motorists realize when they drive on a smoother pavement and (2) savings in maintenance expenditures that the agency (VDOT) will realize (plus the savings in road user cost that motorists will realize) if a smoother pavement enables the agency to defer resurfacing, and the attendant lane closures, for 1 or more years. Attendant increases in the cost of the maintenance contract itself, or in the owner agency's (VDOT's) cost to administer the contract, were counted as costs in the analysis.

RESULTS AND DISCUSSION

Literature Review

Use of Pay Adjustments with a Special Provision for Rideability

The rideability specification, or special provision for smoothness, is a contract line item that provides a payment incentive for the road builder to meet or exceed a target IRI specified by the highway owner. The road builder who produces a pavement with an IRI below the target value is entitled to an incentive payment, or bonus. The builder who produces a pavement with a roughness above the target IRI is subject to a disincentive, or withholding. The rideability specification is one among a variety of performance-related I/D clauses, some of which have seen many years of use (Michigan Technological University, 1994; Riley, 1991).

Legal precedent has established particular principles that govern the enforceability of payment disincentives. First, the amount of the disincentive must be based on a valid computation of the costs or damages that the disincentive is designed to avert, or recover. U.S. law honors contractually specified disincentives even in situations where the actual cost of failing to meet the performance specifications is difficult to measure. However, the disincentive must be tailored to reflect real damages and not merely to punish. Moreover, the costs or damages that the disincentive is designed to avert ought not to be an amount that can be more easily calculated after the fact than estimated beforehand (Harp, 1993). Road user costs and the costs of inspection and contract administration are two common examples of the costs that owner agencies address by means of disincentives.

Second, the literature suggests that the inclusion of an incentive rather than a disincentive alone enhances the enforceability of the disincentive clause. Harp (1993), in a legal study prepared as part of NCHRP Project 20-6, stated that when coupled with an incentive, "the disincentive will be more enforceable in any court action because the disincentive is less likely to be considered a forfeiture"—in other words, the agency/owner's willingness to pay an incentive shows that the disincentive is not an arbitrary penalty but rather a measure of real value to the owner. The provision is therefore less vulnerable to challenge, i.e., less likely to be voided by a court.

Life-cycle Cost Methodology

In addition to the literature specified in the "Methods" section, Mouaket et al. (1992) provided a good example of the agency-cost and user-cost analysis of a pavement treatment. These authors based their findings on the relationship between cost and roughness reported in Zaniewski et al. (1982) and assumed that a pavement will be rehabilitated when it attains a particular *terminal roughness*. (Life-cycle studies often embrace this assumption but seldom put it to the test.)

Roughness and Road User Costs

Although the classic study on vehicle operating costs by Zaniewski et al. (1982) detected no significant impact of pavement smoothness on fuel consumption, recent studies with vehicles more typical of today's fleet did detect such an impact. Zaniewski et al. used the results of a field test of fuel consumption in late-model (i.e., late 1970s) vehicles and a survey of truck fleet owners to relate vehicle operating costs, including fuel consumption, to pavement roughness and a variety of other features (e.g., mean speed, grade, curvature). They measured roughness by the pavement serviceability index and found the following: "In general, there were no statistically significant differences at the 95% level between the fuel consumption on the paved sections." In contrast, at the WesTrack facility in Nevada, a record of the fuel consumption of two test vehicles before and after a pavement rehabilitation in 1998 found that a reduction of 10% in the average IRI was accompanied by a reduction of 4.5% in the fuel consumption of the truck. This difference would save 10,620 gallons of fuel per million truck-miles (Epps et al., 2002; Sime and Ashmore, 2000). Results from a limited test by the Florida Department of Transportation (DOT) indicated that a 10% reduction in roughness would raise fuel economy by about 1.3% (Jackson, 2004). Preliminary data from the National Center for Asphalt Technology (NCAT) Pavement Test Track in Alabama indicated that a 10% reduction in roughness would produce about a 10% reduction in fuel consumption; it is difficult, however, to separate the influence of pavement roughness from the influence of vehicle age in the NCAT data because the roughness of the pavement and the age of the test fleet progressed in parallel during the period these data were collected (Jackson, 2004; Powell, 2005).

Roughness and Costs to Third Parties

Pavement roughness may also affect the emission of combustion products and noise from a highway (see, for example, Hanson et al. [2004]). This study, however, does not attempt to estimate the size of this influence.

Lane Closures and Road User Costs

Pavement resurfacing entails costs to the motoring public as well as to the highway agency (Anderson and Ullman, 2000). A lane of pavement must be closed to traffic while it is undergoing resurfacing. The lane closure will certainly cause a small delay because of reduced free-flow speed through the work zone, and it could cause a much larger delay because of queuing if at any time the traffic volume exceeds the throughput capacity of the work zone.

Length and Duration of Work Zone. The number of lane-miles that a paving crew can resurface per day depends on the plant capacity, the haul distances, the number of haul trucks, the capacity of the paving train, and any other activities (such as milling) that must take place in concert with the paving. The length of the activity area that is closed to traffic depends, in turn, on the number of miles that will be resurfaced during the work shift; the lengths of the longitudinal buffer areas on either side of the activity area depend on the speed of the approaching traffic (VDOT, 2005b). The length of time a lane must remain closed after being resurfaced depends on how soon the temperature of the asphalt decreases to the level at which it is capable of bearing traffic; this depends on the composition of the mix, the ambient temperature during placement, and whether the paving is done during the day or at night.

Computing Travel Time Delay. The travel time delay per vehicle attributable to speed reduction is calculated very easily from the reduction in mean speed and the length of the lane closure. For example, the *Highway Capacity Manual* (HCM) (Transportation Research Board, 2000) recommends that the throughput capacity of two 12-ft-wide lanes designed to accommodate a free-flow speed of 65 mi/hr be assumed to be 4,000 veh/hr if there are no shoulder obstructions or other adverse conditions. The HCM recommends that the capacity of the same facility with one lane closed to traffic be assumed to be 1,500 veh/hr, with approximately a 10 mph reduction in mean speed. The reduction in mean speed from 65 to 55 mph implies that, whereas a vehicle at the free-flow speed would consume 60 min/65 mi, or 0.923 min/mi, a vehicle traversing a work zone in which one of the two lanes is closed will consume 60 min/55 mi, or 1.091 min/mi. Although the length of the lane closure varies from job to job, on an interstate highway with a design speed of 65 mph, it might be 3 mi long. In this case, the travel time delay would amount to 0.168 min/mi $\times$ 3 mi = 0.5 veh-min (or 0.0084 veh-hr) for each vehicle that passes for as long as the work zone is in place.

The travel time delay attributable to queuing is calculated with a bit more effort (Garber and Hoel, 1997). The interested reader may find a simple example calculated in the Appendix.

Cost of Travel Time Delay. The value of 1 veh-hr of delay depends on the average number of travelers (or the average dollar value of freight) in each vehicle and on the value of 1 hr of travel time (see Litman, 2005b). The value of 1 hr of travel time varies, in turn, depending on the traveler's income, the traveler's purpose, and possibly on the degree of congestion (Litman, 2005a). Small and Winston (1999), citing several studies, concluded that travelers typically value in-vehicle travel time during urban commutes at about 50% of their hourly (after-tax) wage; they also cited a finding by Morrison and Winston (1985) that travelers place a much lower value on time during intercity passenger trips. In a survey of several studies, Small and Winston (1999) also found that shippers value truck freight transit time at 8% to 18% per day (i.e., they value each hour at between 1/3% and 3/4% of the value of the cargo), depending on the perishability of the cargo.

Chui and McFarland (1986) used survey data to estimate a "speed-choice" model in which each driver surveyed is assumed to choose a travel speed that minimizes the sum of travel time costs, vehicle operating costs, and accident costs. They inferred from the model that the average value of time for passenger vehicles on four-lane divided highways was \$10.40/hr (in 1985 dollars). Lacking enough survey responses from truck drivers to permit an independent estimate, they applied an inflation adjustment to an older estimate to estimate the value of time for trucks at \$19/hr (in 1985 dollars). In 2006 dollars, these values would be \$19.21/hr and \$35.09/hr, respectively (Bureau of Labor Statistics, 2006b).

By way of example, in February 2006, the average hourly earnings of production workers in the United States was \$16.47/hr (Bureau of Labor Statistics, 2006a). An estimate applicable for commuter traffic could be constructed on the assumption that the average occupancy was 1.2 passengers per vehicle, that the average wage was \$16/hr, and that the value of time was 50% of the wage. Under this assumption, the time cost would be 1.2 passengers per vehicle × \$20/passengers per hour × 50% = \$12/veh-hr.

Roughness, Other Measures of Pavement Condition, and Need for Resurfacing

The modeling of pavement roughness as a function of time is well-established. VDOT has collected data for a number of years to track the evolution of roughness over time (McGhee, 1999, 2005; Reid and Clark, 2004a,b).

The connection over time between pavement roughness and visible pavement distress, however, presents more of a challenge to modelers. Measures of visible pavement distress play the primary role in the decision to resurface or rehabilitate a pavement; the availability of funds plays a significant secondary role. Although roughness is unquestionably correlated with visible measures of distress (Johnson and Cation, 1992), the strength and consistency of the correlation in a given location vary with factors such as climate and traffic loading (Patterson and Attoh-Okine, 1992). Lukanen and Holt (2004) reported that the Minnesota DOT's pavement management system tracks eight types of distress: transverse cracking, long cracking, long joint deterioration, multiple (block) cracking, alligator cracking, rutting, raveling and weathering, and patching. VDOT recently started using an automated distress survey based on video images and tracks the following conditions: longitudinal and transverse cracking (two levels of severity), reflected longitudinal and transverse cracking (three levels of severity), alligator cracking (three levels of severity), bleeding, potholes, patched areas, IRI, and rutting.

Gallivan et al. (2004), who documented the effectiveness of 5-year performance warranties in Indiana, estimated the impacts that the warranties had on roughness and rutting and explicitly compared the service-life implications of these two separately measured impacts. The Indiana DOT selected four quantities—smoothness, rutting, cracking, and friction—as warranty criteria; it eschewed other possible candidates, such as segregation, on the grounds that the measurement of these engineering defects would be more subjective. The study found that a warranty adds 5% to 10% to initial costs but adds about 9 years to service life, for a net agency savings of about 27%. The study estimated and reported separate models for roughness and rutting: both models predicted that the warranty provision would increase the average service life of a pavement from 15 years to 24 years. This explicit comparison between the impact of contract provisions on roughness and their impact on another measure of pavement condition, the only such comparison found in the literature search, is encouraging in that it displays convergence.

Visible distress being the usual determinant of pavement service life, this study depends in effect on inferring future levels of visible distress from the present level of IRI. As has been seen, a number of recent life-cycle analyses (e.g., Mouaket et al., 1992; Weed, 2003) rest on the assumption that "terminal IRI" is a meaningful concept, but more direct empirical assurance that a given future level of IRI corresponds on average to a given future level of visible distress would be desirable. The cumulative evidence, in the literature (Gallivan et al., 2004) and in the data analyzed for this study, is suggestive but less than conclusive.

Supporting Data: Description

Roughness Data

As VDOT's rideability program proliferated, the sheer volume of "ride spec" work prevented VDOT from routinely measuring the initial roughness of newly resurfaced pavements on contracts that did not include the rideability specification. However, during one of the first production seasons with the modern rideability specification (1998), the Non-Destructive Testing Unit of VDOT's Materials Division was able to amass a database of approximately 405 project-lanes (a four-lane divided project would constitute four project-lanes) of new-surface IRI measurements. Of these 405 records, 315 represented work that was not subject to the special provision for rideability.

In early 2005, forty-seven of those records were selected and the corresponding pavements were revisited to establish modern-day IRI measurements. Of those original pavement segments, 21 were last resurfaced under contracts that included no rideability provision and the remaining 26 were among the original ride spec projects. Otherwise, these 1998 projects were specifically selected to be of similar character (i.e., geometric design, design speed, traffic makeup and volumes). All 47 records were from four-lane divided projects, with the vast majority being interstate or U.S. primary projects.

Contract Data Breakdown

A fundamental cost question this study sought to answer was: "Does the rideability specification have an impact on the unit price in the winning bid?" The only two items that are routinely included (i.e., quantified and priced) in a resurfacing contract are asphalt concrete and pavement line marking. Other priced items, such as planing (milling), appear in some contracts. Although it is conceivable that a bidder could adjust the price of some item other than HMA, this price seems the most obvious candidate by far, and the study focused on the bid price per ton of asphalt concrete.

The rideability specification is not the only factor that may affect the bid price per ton of plant mix. The bid price can vary considerably depending on mix type and the other details of the contract. The stone matrix asphalt (SMA) mixes, for example, are much more difficult and expensive to produce and place than are the Superpave® (SM) mixes. VDOT experiences and anecdotes identify the size of the job, the need for an additional structural layer, the requirement of planing, the requirement to use a material transfer vehicle (MTV), and time-of-day restrictions as other features that might affect the bid. It was believed important to include these factors in the data set in order to control for their independent influence on price.

The database constructed targeted all VDOT maintenance resurfacing contracts awarded from 2001 through 2005. This period postdates the introduction of the changes to the rideability provision that were mentioned in the "Introduction": 0.01-mi pay lots, the "percent improvement" mechanism, and the higher potential I/Ds. The winning bids, therefore, should be representative of the contractors' reaction to the current rideability provision. Table 1 summarizes the number of contracts by district and statewide.

The information on each contract includes the awarded quantity and price for every surface mix. Table 2 reports the total number of contract "appearances" (i.e., the number of times a particular mix is assigned to a project) for each surface mix type in the 5-year time span. It further provides the total quantity (tonnage) and weighted average price for each bid item.

These data, which were provided through reports from VDOT's Scheduling and Contracts Division, provided the foundation of the database. In order to begin assessing factors that might influence the prices of each bid item, other information was necessary, including the use of the special provision for rideability, requirements for MTV, and any time-of-day restrictions. Unfortunately, information of this sort is available only from the "memo" field on the resurfacing schedules. As a consequence, considerable time and effort were devoted to supplementing the original contract data with detail from printed matter. To reduce the time and effort required, quantities of specific contract items were recorded only when something relevant to a schedule line item (e.g., MTV required) appeared in the printed document.

When completed, a "schedule breakdown" data table containing1,449 records existed. Although far from describing the application of each bid item in each contract completely, this additional table of information made it possible to assess the proportion of each contract that was

Table 1. Total Contracts Considered (2001 through 2005)

VDOT District	Contracts
Bristol	55
Salem	63
Lynchburg	31
Richmond	74
Hampton Roads	24
Fredericksburg	26
Culpeper	25
Staunton	56
Northern Virginia	49
Total	403

Table 2. Surface Mix Quantities and Costs (2001 through 2005)

Mix	No. Contract "Appearances"	Total Quantity (tons)	Avg. Price (Weighted $)
SM-9.5A	195	3,336,431	37.22
SM-9.5D	196	3,627,626	39.40
SM-9.5E	4	60,900	42.02
SM-12.5A	140	2,275,805	39.30
SM-12.5D	164	1,751,460	38.63
SMA-9.5 (70-22)	6	66,088	54.92
SMA-9.5 (76-22)	3	33,085	69.59
SMA-12.5 (70-22)	17	189,995	57.28
SMA-12.5 (76-22)	24	369,103	67.32
SMA-19.0 (70-22)	8	84,060	53.64
SMA-19.0 (76-22)	4	11,389	59.17
All Surface Mixes	761	11,805,942	40.12

Note: The SMA-19.0 mixes are not typically used as "surface" mixes. However, in numerous contracts, the special provision for rideability was attached to the line item associated with them. *The costs have not been normalized (or indexed) to a base year.*

subject to the rideability specification, requiring an MTV, and/or including time-of-day restrictions. Information on planing (milling) and additional structure was also recorded, although the printed schedules are less definitive with these items (i.e., not specifically stated).

Gasoline Price Data

The Energy Information Administration of the U.S. Department of Energy collects gasoline prices from every region of the nation every Monday and publishes these weekly data (Energy Information Administration, 2006). The researchers retrieved the reported average price of regular grade, conventional formulation gasoline in the Lower Atlantic Region on each of the four Mondays in February for each of the 5 years (2001 through 2005) covered by the contract data set. As VDOT typically awards maintenance resurfacing contracts in February of each year, the average of these four weekly prices in a given year is expected to reflect the year-to-year change in materials costs and to control for the impact of materials costs on the bid price per ton of plant mix. The price of gasoline happens to be tracked in much greater statistical detail than the price of asphalt itself. Moreover, asphalt is a product of the same petroleum "cracking" process that produces gasoline, and an oil refinery can and will extract more gasoline—and less asphalt—from a barrel of crude when the price of gasoline rises.

Relevant Fraction of Virginia Highway System

VDOT was responsible for maintaining 124,680.56 lane-miles of highway as of 2004 (VDOT, 2005a). A small fraction of these are unpaved roads, but nearly all of this mileage will require resurfacing in the next 10 to 15 years. As was noted in the "Introduction," however, circumstances on some highway segments (unpaved, uneven curb and gutter, etc.) make the rideability specification impractical. It is difficult to estimate the fraction that will be suited to the rideability specification.

It is known, however, that for the last several years, VDOT's district offices have been encouraged to apply the rideability specification to every project they considered to be a candidate. If they have done so, the sample of all resurfacing contracts from 2001 through 2005 with the presence/absence of the rideability line item being explicitly noted ought to provide a fair estimate of the proportion of total mileage to which the rideability specification can be applied.

The contract data were extracted from printed resurfacing schedules. Because the format of the schedules made it difficult to identify the number of lane-miles to which each contract applied, the data set does not provide a direct record of the number of lane-miles in Virginia that were resurfaced or the number subjected to the rideability provision. Rather, the number of winning bids and the quantity of plant mix covered by each bid are tallied. (The interested reader may note that when one is resurfacing lanes that are 12 ft wide, a 1.5-in lift requires about 580.8 tons of asphalt concrete per lane-mile.)

The data set covers 761 winning bids and 11,805,942 tons of plant mix. Of the winning bids, 283, or 37.2% of the total, involved work that was subject to the rideability specification in whole or in part. Of the tons of plant mix, 3,059,278, or 25.9% of the total, were subject to the rideability specification. From contracts where the special provision applied to only part of the work, this total includes *only* the tons that were subject to the special provision. Table 3, which is an expansion of Table 2, provides a summary of the data set.

Given that the sample covers 5 fiscal years, the data imply that VDOT advertises and awards some 2.4 million tons' worth of resurfacing work per year, of which one-fourth—about 600 thousand tons—will be subject to the rideability specification. The data suggest moreover that an even larger fraction of the advertisements, at least 37.2%, will include the rideability line item.

Table 3. Summary of Bid Price Data Set

Mix	Contracts with Spec	Percent with Spec	Quantity with Spec	Percent with Spec
SM-9.5A	36	18.5	355,465	10.7
SM-9.5D	95	48.5	1,170,778	32.3
SM-9.5E	0	0.0	0	0.0
SM-12.5A	43	30.7	402,522	17.7
SM-12.5D	68	41.5	607,357	34.7
SMA-9.5 (70-22)	4	66.7	41,981	63.5
SMA-9.5 (76-22)	1	33.3	6,752	20.4
SMA-12.5 (70-22)	8	47.1	76,459	40.2
SMA-12.5 (76-22)	21	87.5	327,743	88.8
SMA-19.0 (70-22)	6	75.0	65,408	77.8
SMA-19.0 (76-22)	1	25.0	4,812	42.3
SM Total	242	34.6	2,536,122	22.9
SMA Total	41	66.1	523,155	69.4
Total	283	37.2	3,059,277	25.9

Note: The apparent discrepancies between the totals at the bottom of the "Quantity" column and the sums of the numbers above them result from rounding to the nearest whole number.

Data Analysis

Impact of Special Provision on Achieved Smoothness and Service Life

The 1998 roughness data collected by VDOT's Non-Destructive Testing Unit were very useful. They provided one of the last opportunities to compare the new-surface ride quality of work done with the special provision for rideability ("ride spec" pavements) and without ("non-spec" pavements). By revisiting a portion of these projects, it was also possible to estimate the typical progression of roughness and to investigate whether use of the provision affected the progression.

For the entire 1998 database, the average new-surface IRI for the 315 non-spec pavement segments was 89.9 in/mi. The average new-surface IRI for the remaining 90 pavements was 80.9 in/mi (a 9 in/mi difference). Among the pavements selected from this database to revisit in 2005, the 26 that were resurfaced under the special provision began life with an average roughness of 67.4 in/mi, with a standard deviation of 10.2; the 21 that were resurfaced without the rideability provision had an average initial roughness of 76.2 in/mi, with a standard deviation of 11.5. In other words, the ride spec pavements started 8.8 in/mi smoother, on average, than the non-spec pavements. In 2005, after 7 years of wear, the ride spec pavements averaged 76.0 in/mi, with a standard deviation of 12.0, and the non-spec pavements averaged 84.9 in/mi, with a standard deviation of 10.6. In both groups, pavement roughness increased over time at a rate of approximately $8.6 \div 7 = 1.23$ in/mi-yr, so that the ride spec pavements were still 8.9 in/mi smoother on average in 2005.

The difference between the means of the two groups was statistically significant, in both 1998 and 2005 (see Table 4). A test of the null hypothesis that the means of the two groups were equal produced a Student's *t* statistic of 2.76, significant at the 0.008 probability level, for the 1998 observations. (If the ride spec and non-spec groups truly came from a common pool—that is, if they were all products of the same process—then there would be such a big difference between the means of the two groups by chance only 0.8% of the time.) Thus, it seems very unlikely that the ride spec and non-spec jobs produce the same results. For the 2005 observations, the test of the null hypothesis produced a *t*-statistic of 2.63, significant at the 0.012 probability level. For the 47 pavement sample, an ordinary least squares regression of the 7-year (2005) roughness on the initial (1998) roughness produced the regression equation $IRI_{05} = 0.9215 \times IRI_{98} + 14.19$, with an R^2 value of 0.7745. The R^2 value shows that some factors other than initial roughness—presumably, factors related to structural soundness, weather, or traffic—accounted for a portion of the change in roughness from 1998 to 2005.

It can be seen that the difference of 8.8 in/mi between the ride spec and non-spec jobs means that after 7 years, the ride spec pavements exhibited the same roughness that the non-spec pavements exhibited when they were new. This difference would imply an additional functional service life of 7 years if—and it must be stressed again that the literature more often assumes it than tests it— the amount of visible distress that normally leads to resurfacing corresponds to a particular average terminal roughness. The researchers have reservations, which they address later in the "Results and Discussion," about inferring such a large impact.

Table 4. Summary of Roughness Data Set and Comparison of Mean IRI

1998	**No Spec**	**Ride Spec**	**Pooled**
Sample Size	21	26	47
Sample Mean	76.1429	67.3846	71.2979
Sample Variance	132.4286	104.8062	117.0828
SD	11.5078	10.2375	10.8205
Difference in Means			8.7582
Variance of Difference (under H_0)			10.0786
SD of Difference (under H_0)			3.1747
t Statistic = Diff / Std Dev			2.7588
Probability (under H_0), df = 45			0.00835827
2005	**No Spec**	**Ride Spec**	**Pooled**
Sample Size	21	26	47
Sample Mean	84.7619	75.9615	79.8936
Sample Variance	112.3905	144.2785	130.1060
SD	10.6014	12.0116	11.4064
Difference in Means			8.8004
Variance of Difference (under H_0)			11.1996
SD of Difference (under H_0)			3.3466
t Statistic = Diff/SD			2.6297
Probability (under H_0), df = 45			0.01165632

Note: Non-Spec = project not subject to Special provision for rideability;
Ride Spec = project subject to special provision.

The findings reported here are consistent with those of historical research, as well as with those of less formal comparisons conducted more recently. Using an extensive database (including ride quality and other project information) from resurfacing conducted in 1996 and 1997, McGhee (1999) identified a consistent 6 to 8 in/mi decrease in IRI for projects that were constructed under the special provision for rideability. In 2004, a fairly limited analysis focused on about 11 mi of HMA that had been placed on the Capital Beltway (I-495) without the benefit of the ride specification. Clark (2005), who at the time was the State Pavement Design and Evaluation Engineer, tested that work and compared it with the constructed smoothness of similar (i.e., high-traffic interstate) projects nearby that were subject to the special provision for ride quality. In a memo sent to the Northern Virginia Construction District, Clark (2005) documented an IRI on the "spec work" of 8 in/mi smoother (lower IRI) than for the non-spec activity.

Impact of Special Provision on Bid Price

Two distinct lines of reasoning might lead one to expect that use of the special provision would raise the bid price. First, if contractors believe they cannot control perfectly the smoothness of the new pavement, they will demand a "risk premium" in exchange for bearing the risk of a bad outcome. Second, if contractors believe they can achieve the target smoothness only by changing their customary methods, then they may ask a higher price to cover the cost of the extra quality controls they expect to implement. The contract award data analyzed in the study, however, do not show conclusively that the rideability provision has an impact on the unit bid price per ton of asphalt concrete.

Preliminary Statistical Evaluation

The statistical results come from a set of 760 observations that include jobs involving five Superpave mixes—SM-9.5A, SM-9.5D, SM-9.5E, SM-12.5A, and SM-12.5D—and six stone matrix asphalt mixes—SMA-9.5 (70-22), SMA-9.5 (76-22), SMA-12.5 (70-22), SMA-12.5 (76-22), SMA-19.0 (70-22), and SMA-19.0 (76-22). (One project that contained a zero in the "Total Quantity" field was omitted.) The A, D, and E designations for the Superpave mixes correspond to a liquid asphalt performance grading (PG) of 64-22, 70-22, and 76-22, respectively.

The variables in the contract data set include (1) project number; (2) mix type, represented by a set of 11 dummy variables; (3) winning bid price in dollars per ton; (4) total quantity of mix, in tons, to which the bid applies; and (5) fraction of the job, also in tons, subject to each of the following line items: (a) a rideability specification, (b) requirement of a MTV, (c) time-of-day restrictions, (d) an additional structural layer, and (e) planing/milling. To this is added (6) the average price of regular grade, conventional formulation gasoline during the four Mondays in February in the year the contract was awarded.

The correlation coefficients among the continuous regression variables revealed no troubling high collinearities. The highest correlation coefficient was between the fraction subject to planing and the fraction subject to time-of-day restrictions: 0.645432. However, a high collinearity between the mix type dummies and one of the continuous variables did exist. Whereas the average fraction of tonnage requiring an MTV was only 0.139 in the entire data set, within the SMA subset the average value of the fraction of tonnage requiring an MTV was 0.877: almost all jobs involving SMA mixes included the MTV line item, and most required the MTV for 100% of the work. This fact *a priori* makes it unlikely that the contract data could identify the influence of the MTV requirement on the bid price of SMA mix, but as the MTV requirement is not the focus of this study, it is not a problem here.

Regression Analysis

The bid price per ton of asphalt concrete was regressed by ordinary least squares on the remaining variables in the set. The regression model assumed simply that the dependent variable was a linear function of the independent (explanatory) variables, of the form $y_i = b_1 \cdot x_{1i} + b_2 \cdot x_{2i} + b_3 \cdot x_{3i} + \cdots + u_i$, where y is the dependent variable (bid price, or log of bid price); x is one of the independent variables, indexed by the numbers 1, 2, 3, etc.; u is an independent identically distributed random error; and $i = 1, ..., 760$ indexes the observations in the data set. Because the fraction of the job subject to time-of-day restrictions was insignificant in all trials, and because the statistical package used (Microsoft Excel) restricted to 16 the number of independent variables in the regression, the time-of-day variable is omitted from the results.

Linear Regression on All Independent Variables. The first regression pooled all of the observations. Table 5 shows the results of the regression analysis. The intercept term, in effect, indicates the expected price of a ton of SM-9.5A when the total quantity is close to zero and the fraction subject to any of the special conditions (ride spec, MTV, etc.) is zero. The coefficients on the mix type dummies reflect expected price differences between SM-9.5A and the other mix types. The coefficient on the gas price variable and the total quantity variable are statistically significant at the 1% level. The winning bid price per ton of plant mix appears to rise by about $1.46 for every $0.10 increase in the price per gallon of gasoline. The winning bid price per ton of plant mix appears to drop by some $0.10 for every thousand tons estimated in the advertisement. The coefficient on the proportion subject to the rideability provision is statistically insignificant: the point estimate is $1.03/ton, with a standard error of $1.31/ton and a Student's *t* statistic of 0.791. To put it in other terms, the 80% confidence interval around the coefficient runs from –$0.64 to $2.71/ton. This implies that the winning bid price appears to rise by about $1.03 when 100% of the job is subject to the ride spec, but that a value of $0.00 cannot be ruled out (even if the impact were truly zero, a statistical finding as big as $1.03 would have a 42.9% probability of occurring by coincidence).

Table 5. Ordinary Least Squares Regression of Bid Price Against (1) Price of Gasoline ($) minus $2.50, (2) Total Quantity (tons), (3) Fraction Subject to Rideability Specification, (4) Fraction Subject to MTV Requirement, (5) Fraction Requiring Additional Structural Layer, (6) Fraction Requiring Planing, and (7) Ten Dummy Variables Representing Mix Types

Regression Statistics			
Multiple R	0.60430031		
R Square	0.36517890		
Adjusted R Square	0.35150846		
Standard Error	10.35528653		
Observations	760		
ANOVA			
	df	**SS**	**MS**
Regression	16	45831.8493	2864.490579
Residual	743	79673.3456	107.231959
Total	759	125505.1949	
	Coefficients	**Standard Error**	**t Stat**
Intercept (SM-9.5A)	55.01635252	1.64908058	***33.36183399
Gas Price	14.67051624	1.42470940	***10.29719898
Total Awarded Qty	-0.00010321	0.00002732	***-3.77848357
Ride Spec	1.03478483	1.30763723	0.79133938
MTV	-1.65648591	1.66948602	-0.99221311
Add. Structural Layer	-3.05609120	3.08495879	-0.99064247
Planing	-0.43067471	1.66618765	-0.25847911
D2 (SM-9.5D)	1.98692197	1.07882154	*1.84175222
D3 (SM-9.5E)	1.64950894	5.23710698	0.31496568
D4 (SM-12.5A)	1.55914457	1.15542334	1.34941412
D5 (SM-12.5D)	2.30847170	1.15988733	**1.99025512
D6 (SMA-9.5 (70-22))	16.67915346	4.44826566	***3.74958574
D7 (SMA-9.5 (76-22))	25.92259236	6.13496178	***4.22538775
D8 (SMA-12.5 (70-22))	16.99455669	2.91208868	***5.83586509
D9 (SMA-12.5 (76-22))	27.59662953	2.68262828	***10.28716118
D10 (SMA-19.5 (70-22))	13.47250953	4.13443205	***3.25861192
D11 (SMA-19.5 (76-22))	24.73823393	5.42409549	***4.56080355

* = *t*-statistic significant at 10% level.
** = *t*-statistic significant at 5% level.
*** = *t*-statistic significant at 1% level.

Loglinear Regression on All Variables. The second regression also pooled all of the observations. In contrast to the first regression, the second used the natural logarithm of the bid price as the dependent variable. The regression coefficients indicate *percentage* changes in the bid price per ton of plant mix rather than dollar amounts. The results of this second regression, not tabulated, are substantively the same as the results of the first, except that the coefficient on the proportion of the job subject to the rideability provision is statistically significant at the 10% level: the point estimate is 0.03872, with a standard error of 0.02056 and a Student's *t* statistic of 1.883. To put it in other terms, the 80% confidence interval around the coefficient runs from 0.01234 to 0.06510. This offers a measure the impact of the ride spec that is independent of price inflation: it implies that the winning bid price appears to rise by about 3.9% when 100% of the job is subject to the rideability provision.

Separate Linear Regressions on SM and SMA Subsamples. The next round of regressions separated the winning bids on SM mixes and the winning bids on SMA mixes into separate subsamples of 698 and 62 observations, respectively. These results are not tabulated. Regression of the SM subsample alone produces a nearly identical estimate of the coefficient on the ride spec proportion, $0.99/ton, with a slightly larger confidence interval than that from the whole sample. Regression of the much smaller SMA subsample alone produces a much larger point estimate of the coefficient on the ride spec proportion, $3.63, with an 80% confidence interval from $0.76 to $6.50.

Test of Hypothesis That Ride Spec Has Same Impact on Bids for Superpave and Stone Matrix Asphalt

As the regressions on the separate SM and SMA subsamples produce somewhat divergent results, it is reasonable to test the hypothesis that the rideability provision has the same impact on bids for SM jobs that it has on bids for SMA jobs. To do so, the researchers introduced two distinct ride spec variables in place of one: the first, equal to the fraction subject to the ride spec *times* an SM dummy variable, could take a non-zero value only when the observation involved an SM mix; the second, equal to the fraction subject to the ride spec *times* an SMA dummy variable, could take a non-zero value only when the observation involved an SMA mix. (In order to add the additional ride spec variable while remaining within the Microsoft Excel package's 16-variable limit, the Planing variable was omitted from the regressions.) Table 6 shows the results of a regression that preserves the restriction that the ride spec coefficient be the same for SM and SMA. Table 7 shows the results of an otherwise-identical regression that removes this restriction, and the *F*-statistic that is computed from the sums of squared residuals in the two regressions.

The lifting of the restriction has almost no effect on the regression results. The two ride spec coefficients take somewhat different point values when the restriction is removed: $0.89/ton within an 80% confidence interval of ±$1.68/ton for the SM mixes versus $1.23 ± $4.38/ton for the SMA mixes. This difference, however, is not statistically significant. The impact that the restriction has on the sum of squared regression residuals is negligible: the *F* test statistic ($F_{744,743}$ = 1.000012205) is so close to unity, the value that would be expected under the null hypothesis that the probability of obtaining an *F* statistic this large by chance is quite good. The null hypothesis that the two coefficients are truly equal cannot be rejected.

Table 6. Ordinary Least Squares Regression of Bid Price Against (1) Price of Gasoline ($) minus $2.50, (2) Total Quantity (tons), (3) Fraction Subject to Rideability Specification, (4) Fraction Subject to MTV Requirement, (5) Fraction Requiring Additional Structural Layer, and (6) Ten Dummy Variables Representing Mix Types

Regression Statistics			
Multiple R	0.60425311		
R Square	0.36512182		
Adjusted R Square	0.35232186		
Standard Error	10.34879025		
Observations	760		
ANOVA			
	df	**SS**	**MS**
Regression	15	45824.6849	3054.978997
Residual	744	79680.5099	107.097460
Total	759	125505.1949	
	Coefficients	**Standard Error**	**t Stat**
Intercept	55.03613423	1.64627036	***33.43079947
Gas Price	14.68874136	1.42207090	***10.32912027
Total Awarded Qty	-0.00010300	0.00002729	***-3.77482842
Ride Spec	0.92751785	1.23926081	0.74844443
MTV	-1.79273200	1.58309652	-1.13242116
Add. Structural Layer	-3.20268464	3.03047705	-1.05682524
D2	1.98795665	1.07813733	*1.84388073
D3	1.64178465	5.23373633	0.31369266
D4	1.54465873	1.15333941	1.33929242
D5	2.25650993	1.14161695	**1.97659113
D6	16.75545180	4.43567646	***3.77742875
D7	25.77020985	6.10273970	***4.22272800
D8	16.87994916	2.87632997	***5.86857188
D9	27.54157339	2.67248121	***10.30561910
D10	13.25058428	4.04176341	***3.27841661
D11	24.69108644	5.41762683	***4.55754655

* = *t*-statistic significant at 10% level.
** = *t*-statistic significant at 5% level.
*** = *t*-statistic significant at 1% level.

It will be evident to the reader that there is a greater degree of uncertainty in the estimate of the ride spec coefficient for the SMA mixes (i.e., the 80% confidence interval is larger). The reader should remember that a smaller sample of SMA bids, 62, was available for analysis. When more observations of bids on SMA jobs become available, it may be possible to estimate the impact of the ride spec more precisely.

Table 7. Ordinary Least Squares Regression of Bid Price Against (1) Price of Gasoline ($) minus $2.50, (2) Total Quantity (tons), (3A) Fraction Subject to Rideability Specification–SM Mixes, (3B) Fraction Subject to Rideability Specification–SMA Mixes, (4) Fraction Subject to MTV Requirement, (5) Fraction Requiring Additional Structural Layer, and (6) Ten Dummy Variables Representing Mix Types

Regression Statistics			
Multiple R	0.60425952		
R Square	0.36512957	SSR(restr):	79680.5099
Adjusted R Square	0.35145806	SSR(unrestr):	79679.5374
Standard Error	10.35568890	F statistic:	1.000012205
Observations	760	F test P-value:	0.49994017
ANOVA			
	df	**SS**	**MS**
Regression	16	45825.6574	2864.103590
Residual	743	79679.5374	107.240293
Total	759	125505.1949	
	Coefficients	**Standard Error**	**t Stat**
Intercept	55.03970465	1.64779440	***33.40204619
Gas Price	14.68931897	1.42303180	***10.32255144
Total Awarded Qty	-0.00010297	0.00002731	***-3.77085390
Ride Spec SM	0.88660018	1.31241834	0.67554693
Ride Spec SMA	1.23087439	3.41844605	0.36006840
MTV	-1.80001256	1.58599567	-1.13494166
Add. Structural Layer	-3.17868056	3.04295556	-1.04460302
D2	1.99587073	1.08205225	*1.84452343
D3	1.63820995	5.23735974	0.31279309
D4	1.54882176	1.15493592	1.34104563
D5	2.26393329	1.14503458	**1.97717461
D6	16.58505449	4.78573816	***3.46551648
D7	25.68453604	6.17272319	***4.16097325
D8	16.76679495	3.11387838	***5.38453752
D9	27.29267212	3.73943048	***7.29861733
D10	13.02688541	4.67716415	***2.78521022
D11	24.63744594	5.45042342	***4.52028109

* = *t*-statistic significant at 10% level.
** = *t*-statistic significant at 5% level.
*** = *t*-statistic significant at 1% level.

Summary: The Cost Added by the Rideability Provision

In the regression analysis of the contract award data, the coefficient on the ride spec quantity does not differ significantly from zero. This means that the contract award data analyzed in the study do not show conclusively that the rideability provision has an impact on the unit bid price per ton of asphalt concrete. The reader must keep that statistical fact in mind.

An honest, conservative estimate of the impact of the rideability provision on VDOT's cost is desirable nonetheless, and zero is not the best estimate. The reader will note that the *point estimate* of the impact of the rideability provision on the bid is $1.03/ton. Although the reader must keep in mind that the 80% confidence interval around this estimate is so large we cannot rule out the possibility that the true impact is zero, \$1.03/ton is a more honest—and more conservative—estimate of the impact.

Under the assumption that the lane of pavement was 4 yd wide and that the new layer of asphalt concrete would be spread at a rate of 165 lb/yd^2 (i.e., 1.5 in thick), the estimated plant mix quantity would be 1,760 lane-yard/lane-mile × 4 yd^2/lane-yard × 165 lb/yd^2 ×1 ton/2,000 lb = 580.8 ton/lane-mile. The cost impact of the rideability provision would therefore be \$1.03/ton × 580.8 ton/lane-mile = \$598/lane-mile, with an 80% confidence band from –\$0.64 to \$2.71/ton × 580.8 ton/lane-mile = –\$372 to \$1,574/lane-mile.

It is reasonable to assume that any cost increase manifested in the award amounts is a fair estimate of the cost increase in the payouts. It is true that data on *completed* contracts would have permitted a more accurate estimate of the ride spec's impact on payouts, and it is also true that studies of *time-based* I/D provisions have found that contractors almost always make or beat the target completion date and collect the maximum incentive (Riley, 1991). However, contract award data were easier to retrieve in quantity than were payout data. Further, VDOT statistics indicate that in the past few years the total incentives paid out under the terms of the special provision for rideability have roughly equaled the disincentives withheld under the provision (Reid and Clark, 2003).

The Value Added by the Rideability Provision

The justification for tying a payment I/D to IRI at completion of work is that a higher initial surface smoothness leads to cost savings for the agency that maintains the highway, for the travelers and carriers who use it, and/or for the people who live and work close enough to the highway to be affected by pollutant emissions (e.g., tire noise or combustion gases) from it.

Service Life and Resurfacing Cost

VDOT data indicate that when working under a contract with a rideability specification, road builders produce pavement that is on average smoother, by 8.8 in/mi, than the pavement they deliver when working under similar conditions without such a specification. The difference is statistically significant. The data further indicate that a surface produced under the specification has, when 7 years old, the same average IRI as does a newly placed surface produced without it. These findings can be construed to mean that the rideability specification "turns back the clock" on IRI by about 7 years. As noted earlier, however, visible distress generally determines the service life of a pavement: what impact does the improved smoothness of a newly placed surface have on its service life?

Given the very limited empirical evidence correlating the progress of IRI over time with the progress of measures of distress over time, to assume that delaying the progress of IRI by 7 years will delay the progress of cracking, rutting, or raveling by an equal amount is not prudent. Service life depends on load-related aging, which roughness influences, and on environmental aging, which roughness probably does not influence. *The Mechanistic-Empirical Pavement Design Guide* (ERES Consultants, 2006) uses the initial as-constructed IRI as an input to model the development of pavement roughness over time. Other inputs to that model include rutting, bottom-up/top-down fatigue cracking, thermal cracking, and other climatic factors. Although the comprehensiveness of the guide's smoothness prediction capacity supports the concept of a "terminal IRI," more local experience (i.e., within Virginia) is that pavements generally do not achieve a terminal roughness level prior to reaching some less "superficial" threshold (e.g., fatigue cracking, etc.). One may more plausibly attribute to the empirically observed smoothness improvement of 8.8 in/mi an increase in service life of something like 2 years. If the expected service life of a typical pavement is assumed to be 10 years—the number that Weed (2002) adopts as "reasonable"—one may then plausibly attribute to the specification an increase in service life from 10 years to 12.

Any increased service life implies that the agency, VDOT, will be able to put off the costs of resurfacing the road. In the maintenance resurfacing contracts that VDOT awarded in January and February of 2006, the average price of SM-9.5D, the most-used plant mix, was \$52.23/ton (Kiefer, 2006). The regression results, which predict that SM-9.5D would cost about \$54.20/ton given the price of gas in February 2006, match this reasonably well. Resurfacing 1 lane-mile of pavement may therefore be assumed to cost about \$30,347 (a 1.5 in lift, in other words 580.8 tons, at \$52.25/ton) for VDOT. The rideability provision, by deferring resurfacing for 2 years, can reduce the present value of the next overlay from 74.4% of the current cost (the 10-year discount factor at 3%) to 70.1% (the 12-year discount factor at 3%). This saving, then, is worth (74.4% - 70.1%) × \$30,347/ln-mi = \$1,295/ln-mi. In the long term, the habitual use of the rideability provision with those roads where it is applicable can reduce VDOT's annual maintenance outlays on those roads to about 10/12 of what they otherwise would have been, assuming a 2-year life extension.

The transitory presence of the work zone imposes additional time and fuel costs on the motorists who drive the road. The value of these additional costs depends heavily on the traffic volume on the road that is resurfaced. In the example computed in a previous section, "Cost of Travel Time Delay," for example, closing one of the two lanes in one direction on a divided highway reduced the capacity from 4,000 to 1,500 veh/hr and reduced the free-flow speed by 10 mph. If the lane closure were 3 mi long and the traffic volume were 1,500, 1,600, 1,500, and 1,400 veh/hr during the 4 hr studied (these values are assumed only because they make the computation as simple as possible), the reduced speed would add 0.0084 hr/mi to each vehicle's travel time: 6,000 vehicles × 0.0084 hr/mi × 3 mi = 150 veh-hr. The queuing would impose another 200 veh-hr. This travel time cost would have a value on the order of \$12/veh-hr × 350 veh-hr = \$4,200. It is easy to see that the work zone need not be of very long duration or the traffic volume very big to create road user costs equal to 10% or more of the agency cost.

Roughness and Road User Cost

The 1998 data from VDOT's Non-Destructive Testing Unit further suggest that the rideability specification reduces the IRI of a newly placed overlay from an average of 76.2 in/mi to an average of 67.4 in/mi. After 7 years, the difference appears to be nearly the same: 84.9 in/mi for an overlay placed without the specification versus 76.0 in/mi for an overlay placed with it. If the responsible agency were to continue to resurface the road on the10-year cycle posited by Weed (2002), the average roughness of the pavement would be about 12% lower as a result of the rideability specification. If, on the other hand, the agency were to resurface the road on a 12-year cycle, taking advantage of the increase in service life noted previously, the average roughness of the pavement would be about 10% lower as a result of the rideability specification.

The classic report on road user costs by Zaniewski et al. (1982) found no perceptible correlation between pavement roughness and fuel consumption per vehicle-mile. However, more recent reports from WesTrack (Sime and Ashmore, 2000; Epps et al., 2002) and the Florida DOT (Jackson, 2004) and unpublished data from NCAT (Jackson, 2004; Powell, 2005) suggest that a 10% reduction in IRI will cause a reduction in fuel consumption of from 1.3% (Florida DOT) to 4.5% (WesTrack) to 10% (NCAT). Each 1% reduction in fuel consumption will save truckers about 2,360 gallons per million *truck*-miles. At a price of $2.38/gal, the nationwide average for the first half of March 2006, the savings have a value of $5,616.80 (Associated Press, 2006). This account ignores the possible benefits of lower combustion emissions to third parties.

The Trade-Off Between Increased Service Life and Reduced Roughness

The empirical findings imply that the highway agency faces a trade-off in choosing how to capture the benefits of the rideability specification. The agency can resurface the road as often as it ever did, capturing all of the cost savings that result from a smoother pavement but none of the savings that result from a longer service life. On the other hand, the agency can resurface the road less often, capturing some of the savings that result from a longer service life but less of the savings that result from a smoother pavement.

CONCLUSIONS

- *An impact on bid price of VDOT's Special Provision on Rideability cannot be confirmed statistically.* However, on average and for the period covered by this study, the bid price for 1 ton of plant mix that was subject to the rideability provision was $1.03 higher than that of mix not subject to the provision.

- *The use of VDOT's Special Provision for Rideability does not appear to impact the rate at which pavements accumulate roughness.* "Ride spec" and "non-spec" projects accumulate about 1.23 in/mi IRI roughness per year.

- *The use of VDOT's Special Provision for Rideability may add as much as 7 years to the functional life of a pavement*. Surfaces that are placed using the provision start life and maintain an IRI of almost 9 in/mi less (smoother) than do non-spec pavements.

- *If a service life increase of only 2 years is assumed on the network of projects for which VDOT's Special Provision for Rideability is appropriate, habitual use of the provision can reduce annual maintenance outlays by about 15% for those roads where it is used.*

- *The price of plant mix appears to drop by some $0.10 for every thousand tons estimated in the advertisement and rises by $1.46 for every $0.10 rise in the price per gallon of gasoline.*

The quantity of a material and the price of gasoline were the only statistically significant variables of influence on HMA bid price.

RECOMMENDATIONS

1. *VDOT pavement managers at every level should continue to develop, promote, and apply VDOT's Special Provision for Rideability (Reid and Clark, 2003).*

2. *The Virginia Transportation Research Council (VTRC) should work with VDOT's Materials and Asset Management Divisions to develop the empirical link between the quantifiable, but not readily visible, measures of roughness and the visible, but not readily quantifiable, signs of distress.* This effort may take place within the context of validating the distress (and roughness) models from the *Mechanistic-Empirical Pavement Design Guide* (ERES Consultants, 2006).

3. *VTRC should work with VDOT's Materials Division to update the pay adjustment levels for ride quality.* The findings reported herein provide a more rational and scientific basis for incentives/disincentives for constructed smoothness.

4. *The Non-Destructive Testing Unit of VDOT's Materials Division should continue to monitor the roughness of the 47 pavement segments in its experimental study group for as long as the segments are exposed.*

BENEFITS AND COSTS ASSESSMENT

Because user cost computation depends of the volume and composition of traffic, only an example is possible. A realistic computation of the potential cost savings to be captured with the rideability specification is provided here using the following example.

> Consider the 6.32-mi segment of I-64 in Louisa County, Virginia, between the U.S. Route 250 interchange and the State Route 208 interchange. This is a four-lane divided highway that carried in 2004 an average of 14,000 veh/day in each direction (VDOT Mobility Management Division, 2004): 13% of the vehicles were trucks, and the majority (11%) were tractor-trailers. Suppose that this segment is currently resurfaced on a 10-year cycle. The cost added by including a rideability specification in the next resurfacing contract would be about $598 per lane-mile, as estimated previously. What would the cost savings be?

Ten-Year Cycle Continued

If the 10-year resurfacing schedule is left unchanged, the maintenance cost will remain the same whether or not the rideability specification is used and there will be no cost savings attributable to longer service life. In any given year of the 10-year service life, however, pavement placed under the rideability specification will be almost 12% smoother than pavement placed without the specification would have been. Even under the rather conservative assumption that truck drivers experience the increased fuel efficiency measured by WesTrack—$5,616.80 per million truck-miles per 1% reduction in roughness—while drivers of passenger vehicles experience none, the rideability specification would save 28,000 veh/day x 13% trucks/veh x $5,616.8/(million truck-miles × 1% red'n in IRI) x 12% reduction = $245.34/mi-day due to reduced fuel consumption, or $89,550/mi-yr. Discounted at a 3% real rate (discount factor 8.53), these fuel cost savings would have a present value of $763,862 over the following 10 years.

Cycle Extended to Twelve Years

A parallel computation of the cost savings captured in the extended 12-year life cycle for the same hypothetical segment of road would be as follows. The 12-year regime with the rideability specification will confer the same fuel cost savings on motorists for the first 10 years. However, the 12-year regime allows the pavement to deteriorate for 2 more years to a point where the average roughness over the 12-year cycle will be only about 10% smoother than it would have been without the specification. As a consequence, the fuel cost savings in the long run will amount to only $204.45/mi-day or $74,624/mi-yr. The present value of these smaller annualized fuel cost savings is $636,550 over 10 years. (A more rigorous adherence to the 10-year time horizon would stipulate that there is a savings of $763,862/mi over the first 10 years, just as in the 10-year maintenance cycle, offset by a negative "residual value" to account for the higher fuel costs beyond the 10-year horizon).

Changing from a 10-year resurfacing schedule to a 12-year schedule, however, means deferring the expense of resurfacing for 2 years. If resurfacing is assumed to cost $30,347/lane-mile, or $121,387/mi for the four-lane road, the present value of the next resurfacing expense is reduced from $90,324/mi (the value of a $121,387 payment 10 years in the future discounted at 3% per annum, a factor of 74.41%) to $85,141/mi (the value of the same payment 12 years in the future, a factor of 70.14%). This is a maintenance cost saving of $1,295 per lane-mile, or $5,183 per 4 lane-miles.

The time cost that resurfacing imposes on motorists who must drive through the work zone can be computed in the manner described in "Lane Closures and Road User Costs." This cost can be very large on a heavily traveled road or negligible if the work zone does not cause a queue to form. On the hypothetical 1-mi segment of four-lane highway, the peak-hour flow would probably be about 1,400 veh/hr in each direction—not high enough for a one-lane closure to cause a queue to form. Therefore, the travel time cost of a 3-mi lane closure lasting 1 day in each direction would be 0.5 min for each vehicle, or 233.33 veh-hr total. Using Chui and McFarland's (1986) values of time, updated to 2006 dollars, this delay would have a value of 30.33 truck-hrs × $35.09/hr = $1,064.40 plus 203 auto-hrs × $19.21/hr = $3,800.60, a total of $4,964. Changing from a 10-year resurfacing schedule to a 12-year schedule reduces the present discounted value of the travel time cost of the next resurfacing from $3,694/mi (the value of a $4,964 payment 10 years in the future, discounted at 3% per annum) to $3,482/mi (the value of the same payment 12 years in the future). This is a travel time cost savings of $212 per 4 lane-miles.

The agency costs and user costs of resurfacing the hypothetical segment total $97,491. The present value of the next resurfacing, 10 years in the future, is $72,541. The cost savings of deferring the next resurfacing from 10 years to 12 years total $4,164, or 5.7% of the present value.

If this example were representative of the nearly 600,000 tons (or approximately 1,033 lane-miles) that are placed each year using the rideability specification, the total annual maintenance cost savings would be on the order of $1.075 million.

The Trade-Off

In summary, on our sample four-lane segment the 10-year maintenance cycle achieves from the rideability specification a $763,862 fuel cost saving per mile over 10 years and no maintenance cost savings. The 12-year cycle achieves over the same time frame a $636,550/mi fuel cost saving, a $4,164/mi maintenance cost savings, and a $212/mi travel time savings. The trade-off between fuel cost savings and maintenance cost savings is obviously not one-for-one. The reader will recognize, however, that the highway agency realizes the maintenance cost savings while the motoring public realizes the fuel cost savings. Given the fiscal constraints within which a highway agency operates, it cannot be assumed that policy-makers will be able to trade agency costs and user costs one-for-one.

Under either schedule, 10 years or 12, the present value of the cost savings far outweighs the estimated added up-front cost of $598 per lane-mile x 4 lanes = $2,392/mi. Under the 12-year schedule, the present value of the agency cost savings (i.e., maintenance cost) alone is nearly twice the added up-front cost.

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APPENDIX

COMPUTING THE TRAVEL TIME DELAY THAT RESULTS FROM A QUEUE

Figure A-1 illustrates the travel time delay calculations. A queue will begin to grow when first the flow rate exceeds the capacity of the work zone; will begin to shrink as soon as the flow rate, V(t), falls below capacity, C; and will vanish some time later. If the size of the queue is plotted as a function of time, with the number of hours passed on the x-axis and the number of vehicles in the queue at that time on the y-axis, the area between the curve and the x-axis measures the delay in vehicle-hours.

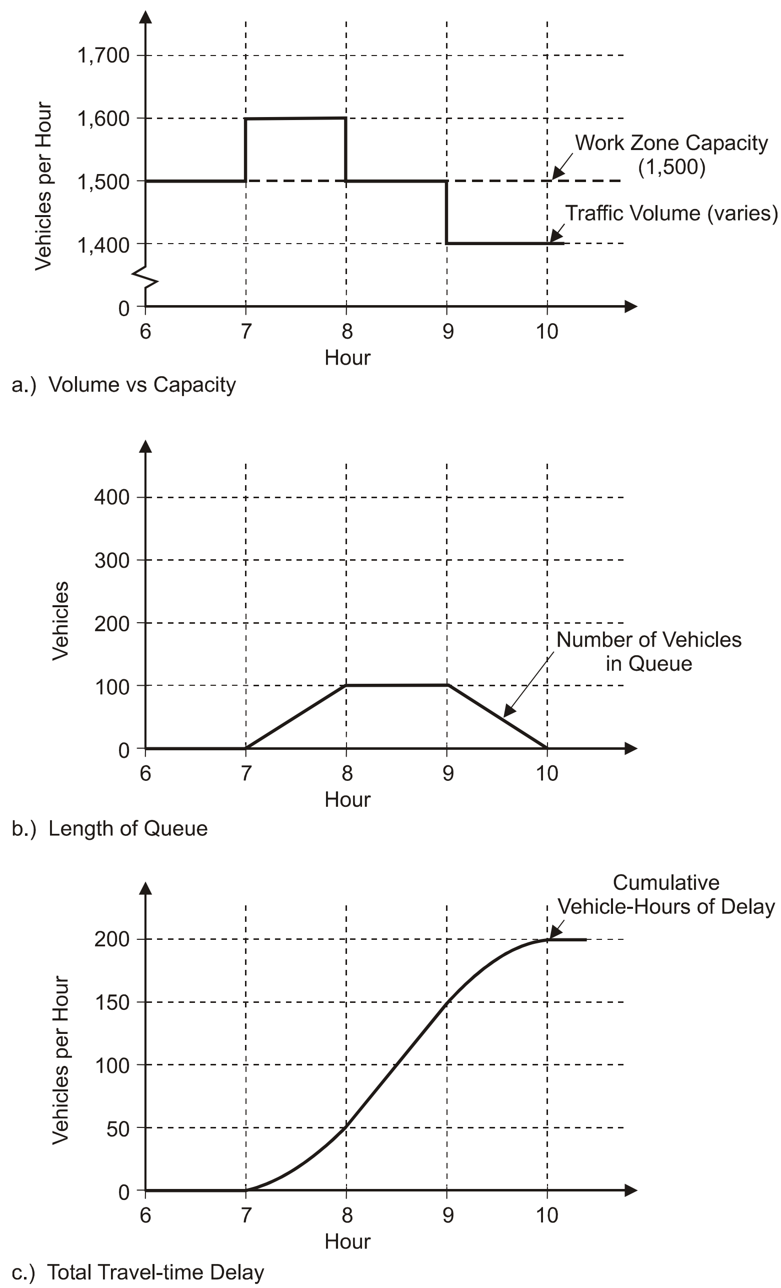

Figure A-1. Steps in Computing Travel Time Delay That Results from a Queue

Using the same example from the HCM, the reduction in capacity from 4,000 veh/hr to 1,500 veh/hr implies that the closure of one of the two lanes will impose an additional queuing cost on motorists if at any time the traffic volume exceeds 1,500 veh/hr. For example, if the traffic averages 1,500 veh/hr during the hour from 6 to 7 o'clock, 1,600 veh/hr during the hour from 7 to 8, 1,500 veh/hr during the hour from 8 to 9, and then 1,400 veh/hr during the hour from 9 to 10, the following will occur. A queue will begin to form at 7, grow to 100 vehicles from 7 to 8, remain at 100 from 8 to 9, and shrink out of existence from 9 to 10. If the queue length is plotted versus time, the area between the curve and the x-axis consists of three parts: a triangle with a base 1 hr long and a height of 100 cars, covering the hour from 7 to 8; a rectangle with a base 1 hr long and a height of 100 cars, covering the hour from 8 to 9; and a triangle with a base 1 hr long and a height of 100 cars, covering the hour from 9 to 10. The area of each triangle is $\frac{1}{2} \times 100$ veh $\times$ 1 hr = 50 veh-hr, and the area of the rectangle is 100 veh $\times$ 1 hr = 100 veh-hr, so the total travel time delay attributable to queuing during the morning is computed to be 200 veh-hr.