Development of performance based pay adjustment factors in Texas, USA

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Abstract

Texas Department of Transportation (TxDOT) currently uses a pay adjustment factor (PAF) system for production and placement of Hot Mix Asphalt (HMA) and ride quality of HMA that has been in existence for almost a decade. A reward/penalty of a contractor according to the current PAF system is based on the offset to the average contractor's performance, which was calculated based on the historical data reflecting contractor's capabilities. However, the average performance of contractors is arguably raised in the past few years due to the improved quality control with the advent of modern equipment in pavement construction. Consequently, current PAFs may be skewed resulting in PAFs those mostly greater than 1.0.

TxDOT sponsored a research project in an effort towards validating the existing pay adjustment system and modifying the same based on performance considerations. The study team developed a comprehensive database by integrating construction quality and pavement management databases. The database summarizes information from about 1500 hot mix surface projects across the State of Texas; it assisted the researchers in thoroughly understanding Texas pavement construction contractors' behavior and examining the relationship between measurable construction quality control parameters and corresponding pavement performance. The study team has developed econometric models in an effort towards understanding such causal relationships (or statistical associations). Researchers utilized various performance criteria such as deterioration rate based on surface roughness, accumulated cracking and rutting at the end of a three year period starting from the construction date. The paper summarizes the findings of a statistical analysis highlighting the measurable quality control parameters that are primarily governing pavement performance. A brief outline of the anticipated future work in developing performance based pay adjustment factors using the aforementioned statistical models is also provided.

Keywords: Pay Adjustment Factor, performance-based

1. Introduction

The tradition of contracting for construction of public roads in USA dates from at least 19th century. Construction specifications evolved as an essential component of contract since that time. The earlier specifications involved only a prescription of materials and required construction methods, which are named as traditional specifications (Chamberlin, 1995). In early 1950s with the beginning of Interstate System and the burgeoning capital expenditure for highway infrastructure after the World War II, the larger companies started contracting in the highway projects (Chamberlin, 1995). As a result, several new sophisticated construction technologies had emerged in that period and most of them were developed by contractors. However, the traditional method specifications retarded such developments in the industry. Moreover, the non-uniformity (vary based on local jurisdiction) and non-applicability of general construction methods for project specific requirements caused several deficiencies in the construction quality. In the early 20th century, American Association of State Highway Officials (AASHTO) helped in developing relatively uniform specifications across different states in USA in consensus with American Society of Testing and Materials (ASTM). Subsequently, in early 1960s AASHTO road test demonstrated the inherent variability in highway construction process and highlighted the rare possibility of 100 percent compliance. Consequently the statistical end result specifications were evolved eventually to replace the traditional specifications using engineering judgment of the quality at construction site. Several states across USA have not implemented the statistical end result specifications until early 1970.

The fundamental intention of any construction specification has been ensuring the expected long term performance of the finished product. A construction project that deviates from the required

quality level should always have a reduced payment than bid price in order to recoup the cost incurred by the agency for additional future maintenance costs. On the other hand, a project with superior quality (more than acceptable level) must be rewarded based on actual saving to the agency corresponding to improvement in performance due to higher construction quality. Despite the advent of sophisticated quality control procedures in the highway industry several agencies started realizing that, statistical end result specifications have not provided the quality assurance once thought. The knowledge of relationship between measurable quality control parameters and long term performance is arguably essential in assessing the quality of any construction job. Subsequently, research communities identified the necessity for more restrictive performance related specifications (PRS) in highway industry. It is important for any highway agency to establish a harmonious relationship with the local construction contractors, while assuring the consistent superior products. This is achievable by rewarding/penalizing contractors based on the actual losses/benefits to the highway agency; PRS implementation ensures such rational pay adjustment system. The main goal of any PRS is not to improve the quality of construction, but to improve the specifications by determining what best reflects the quality and to create a contractual framework that maximizes the cost effectiveness (Chamberlin, 1995).

In USA, Texas Department of Transportation (TxDOT) is sponsoring a research project in an effort towards modifying the existing pay adjustment system based on performance considerations. The study team developed a comprehensive dataset to thoroughly understand Texas pavement construction contractors' behavior and to examine the relationship between measurable construction quality control parameters and corresponding pavement performance. This paper presents the adopted framework for developing such relationship and to quantify the sensitivity of several construction parameters on the pavement performance. Researchers used econometric techniques for identifying the statistical association between the quality control parameters and the pavement performance.

The rest of the paper is structured into six sections. Section 2 presents a review of chronological developments in developing PRS performance models and identifies the specific contribution of this study to the existing literature. Section 3 provides an overview of the methodology for establishing the relationship between quality control parameters and the corresponding pavement performance. Section 4 describes the dependent and independent variables and discusses a few interesting characteristics of the dataset utilized for the study. Section 5 describes the statistical modeling framework and estimation procedures employed by the study team. Section 6 provides a comprehensive discussion on model estimation results. Finally, section 7 highlights the major findings and reports the limitations of the study.

2. Background

The research towards the development of relationships between construction quality measures and performance has not been implemented until early 1980s (Chamberlin, 1995). First and foremost National Cooperative Highway Research Program (NCHRP) synthesis report on statistical oriented end result specifications was published in the year 1976. Subsequently, fundamental concepts behind the PRS and pay adjustment schedules were developed and well documented in the late 1970's to early 1980's (Irick, 1988; Welborn 1984; Majidzadeh et al., 1984; Von Quintus et al., 1985; Shah, 1987; Weed, 1989). In 1980, a new research program is initiated by Federal Highway Administration (FHWA) with two major objectives. Firstly, to

identify the existing specifications that relate to the performance and to develop a complete system for performance related specification for both flexible and concrete pavements (Mitchell, 1981). Secondly, to provide a rational basis for pay adjustment plans, this had been based primarily on experience. In 1984, an extensive literature review conducted by first two FHWA contracts under the research program found lack of models to predict the performance from the existing measurable quality control parameters variables. Consequently, in the year 1985, AASHTO sponsored NCHRP project 10-26 with an objective to identify the variables that are measurable during routine construction quality control and associated with the future performance. The project highlighted the inadequacy of databases in those days for developing required PRS models. In 1986, as part of NCHRP project 10-26A, it was recommended to develop performance models using the laboratory and field performance data from ongoing Strategic Highway Research Program (SHRP), NCHRP projects and Long Term Pavement Program (LTPP). Irick (1988 & 1990) identified the necessity to develop the relationship between measurable quality control parameters and performance indicators.

In 1994, FHWA funded West Track project to further develop performance related specifications. As part of the project, accelerated testing of 34 experimental Hot Mix Asphalt (HMA) pavement test sections is carried out for 2.5 years on a closed loop test track facility (1.75 miles length), which is located approximately 100km southeast of Reno in Nevada desert. It produced adequate data for the refinement of existing performance relationships in order to better account for the influence of off-target values for different measurable construction quality control parameters. Several factors are considered in the experimental design such as, coarse aggregate type, aggregate gradation, asphalt binder type, asphalt content, air void content and thickness of the asphalt layer. Epps et al. (2002) briefly discussed the development of both regression and mechanistic performance models used for fatigue and permanent deformation during the WesTrack project. Fatigue cracking was found to be dependent on asphalt content, aggregate gradation and compaction based on both laboratory and field results, whereas the permanent deformation was dependent on asphalt content, compaction level and pavement temperature.

In 1999, NCHRP 9-15 project was initiated with an objective to identify construction related quality characteristics and as produced HMA quality characteristics those influencing the long term pavement performance. Based on the test results obtained during field experiments (from different projects in Colorado and Illinois) and literature review & surveys, five quality characteristics for HMA pavements were identified for successful incorporation in PRS based on their importance in determining overall performance of HMA pavements; they are ride quality, in-place density, in-place permeability, longitudinal construction density and segregation. It is to be noted that, out of these five, in-place air voids and ride quality are in use for pay factor calculations in Texas. In 2000, the NCHRP project 9-22 considered the possibility of incorporating Mechanistic and empirical design guide (MEPDG) in HMA PRS system. But, it was proved that, the MEPDG approach is too complex for implementation. Consequently, the project developed Quality-Related Specification Software (QRSS) that calculates predicted HMA pavement performance in terms of both fatigue and permanent deformation using measurable quality control parameters as input variables for both as-designed and as-constructed pavement. The stochastic predictions are implemented using Monte Carlo simulations in order to account for construction variability in the quality control parameters. Also, Popescu et al. (2006)

demonstrated a procedure (that is being used by California DOT) for developing performance based pay adjustment schedule using performance prediction models that were developed based on mechanistic-empirical pavement analysis and SHRP developed laboratory test data. They mentioned that air void content, binder content, aggregate gradation were important for rutting performance, on the other hand, air void content, binder content and thickness of the HMA layer for fatigue cracking.

Based on the abovementioned studies, a majority of the PRS development was based on performance data collected from either pilot pavement construction projects or the models built based on the experimental pavement sections. Monitoring the performance of the HMA pavements that are directly delivered by the contractors arguably provides a realistic performance data and thereby assists in building PRS. In author's knowledge, there were only a few former studies that have utilized such contractor delivered pavement performance data in building performance models for PRS framework. For instance, Choi et al. (2004) highlighted the use of Pavement Management Information System (PMIS) databases in developing PRS for Wisconsin DOT projects. They recommended the development of performance models using the PMIS databases to better reflect the local condition (environmental, traffic etc.) in the performance predictions. The formulation of performance models was achieved using linear regression on several quality control parameters (such as air voids, asphalt content, percent passing through No.200 sieve and age of the pavement).

Availability of the relevant databases is of paramount importance for building the relationship between the quality control parameters and the respective pavement performance. Monismith et al. (2004) mentioned that it is important to link material and performance related databases for a gradual transition from the experience based pay factor calculation. They also highlighted the importance of PRS in revealing the relative significance of quality control parameters, which, in turn, enhances the awareness among contractors and agencies to improve the uniformity in performance-related quality characteristics. Choi et al. (2004) also recommends a separate contract support system that is based on existing databases consisting of construction data, performance, Quality Control/Quality Assurance (QC/QA) information, traffic and environment data.

The present paper adds to the literature by presenting the Texas's efforts in developing relationships between construction quality control parameters and pavement performance by integrating project-level QC/QA and network-level performance related databases (PMIS). The models presented in this paper are expected to be used as part of the TxDOT's PRS implementation.

3. Methodology

The primary intention behind rewarding or penalizing a road contractor is to "equally" distribute the benefit/risk of a superior/inferior construction practice between the agency and the contractor. In general, the highway agencies rewards/penalizes during the project construction period, i.e. during (or at the end of) the contracting period. The agency has no knowledge of the future performance of the as-constructed pavement at the end of the contracting period (or immediately after construction). However, the agency does have knowledge about the as-constructed quality of the pavement in terms of routinely measured quality parameters. Intuitively, the future performance of the pavement is dependent on the as-constructed quality

while controlling for the other parameters influencing pavement deterioration. The agency may utilize the available knowledge on the quality control parameters to draw conclusions on the future performance of the project contingent on the existence of a relationship between them. The research team investigated the possibility of developing a relationship between the future performance and the routinely measured quality control parameters. A methodology was developed to understand the existence and strength of the aforementioned relationship by exploring the available knowledge. The methodology attempts to identify/gather two types of information: 1) performance of a given pavement, 2) as-constructed quality of the pavement.

In general, a newly constructed overlay is expected to maintain a minimal deterioration rate with almost no signs of distresses during the first three year period of its life span. The study team developed various performance indices to gauge a projects' performance within the first three year period immediately after construction. These project-level indices are calculated by aggregating the first three year performance data in terms of deterioration rate (of ride), rutting, cracking, flushing and raveling obtained from the Pavement Management Information System (PMIS). Thus, project-level indices aggregate the three year performance data for a given pavement section. On the other hand, quality control parameters such as plant-produced mixture properties and field compaction density are recorded during the construction period per lot on a daily basis. The quality control parameters are also aggregated to obtain a project-level measure of the as- constructed pavement quality. It is to be noted that each project is regarded as one observation in such a project-level dataset. Finally, the empirical relationship between project-level performance and quality control parameters is developed using econometric techniques. The sensitivity of each quality control parameter that governs the performance can be calculated using the empirical models. In conclusion, the methodology assisted the researchers to identify the quality control parameters that are associated with the performance during the first three year period following construction.

It is to be noted that, the proposed methodology currently focusses on immediate failures of HMA projects within a three year span. However, the methodology can be easily extended to long term performance by including more than three years of performance data as the PMIS data becomes available with time. The proposed framework may be easily adopted by any agency that logs project-level QC/QA and network-level PMIS data.

4. Data

The study team linked two of the TxDOT's major pavement databases to form an integrated database that caters the data requirements of this study: 1) Site Manager (SM)—a database that logs quality control parameters, 2) PMIS—a database that logs annual pavement performance. The integrated database includes project level information including averaged construction quality control parameters (volumetric properties of mixture, initial ride, etc.) and the field performance (rutting, cracking and rate of deterioration) of 614 HMA overlay projects in Texas. A detailed description of the dataset including various interesting characteristics and descriptive statistics is provided below.

Table 1 provides a list of variables included in the analysis and reports important descriptive statistics. Seven performance indicators are calculated and reported, but three of them are utilized in the analysis for the reasons explained in the later part of this paper. Apart from the deterioration rate, the remaining performance indicators are binary switch variables (takes either

1 or 0). The binary variables are calculated using the PMIS rutting, cracking, raveling and flushing information aggregated over the three year period immediately after the construction year. For instance, rutting performance indicator variables switches to '1' for a pavement exhibiting any early rutting (during the first three year period immediately after the construction). Researchers opted not to use absolute magnitudes of rutting and cracking considering the relatively higher variability of these rut and crack measurements in PMIS. Availability of reliable rutting and cracking data is essential for modeling deterioration in terms of rutting and cracking. Data suggests that more than 50% of the projects have shown some signs of rutting, cracking and flushing. The exact proportions of projects with some signs of the aforesaid distresses are provided in Table 1. The descriptive statistics provided in the table indicate the following information: 1) about 80% of the projects have exhibited some sign of rutting, 2) about 90% of the projects have exhibited some sign of longitudinal cracking, 3) about 80% of the projects have exhibited some sign of alligator cracking, 4) about 53% of the projects have exhibited some sign of transverse cracking, 5) about 56% of the projects have exhibited some sign of flushing, 6) about 18% of the projects have exhibited some sign of raveling. Authors acknowledge the fact that these numbers are generated based on the following assumption; a project containing a sign of distress anywhere along the total length of the project is categorized as a project exhibiting that distress.

On the other hand, deterioration rate is estimated using a linear regression approach combining the first three year ride quality data (IRI). The slope of the estimated linear regression line is taken as the rate of deterioration; while the estimated value of the IRI during the year of the construction is reported as the initial IRI value (which is used as one of the explanatory variables). Deterioration rate is censored at zero for all the projects with minor deterioration rate (close to zero). Thus, projects are categorized into two groups: 1) No deterioration in first three years, 2) Some level of deterioration. Figure 2 shows a histogram of the deterioration rate for all 614 projects. According to the histogram, about 200 projects did not exhibit any signs of deterioration (or contained minor deterioration). The deterioration rate varied from 0 to 52 inch/mile/year with an average rate of deterioration of 5 inch/mile/year.

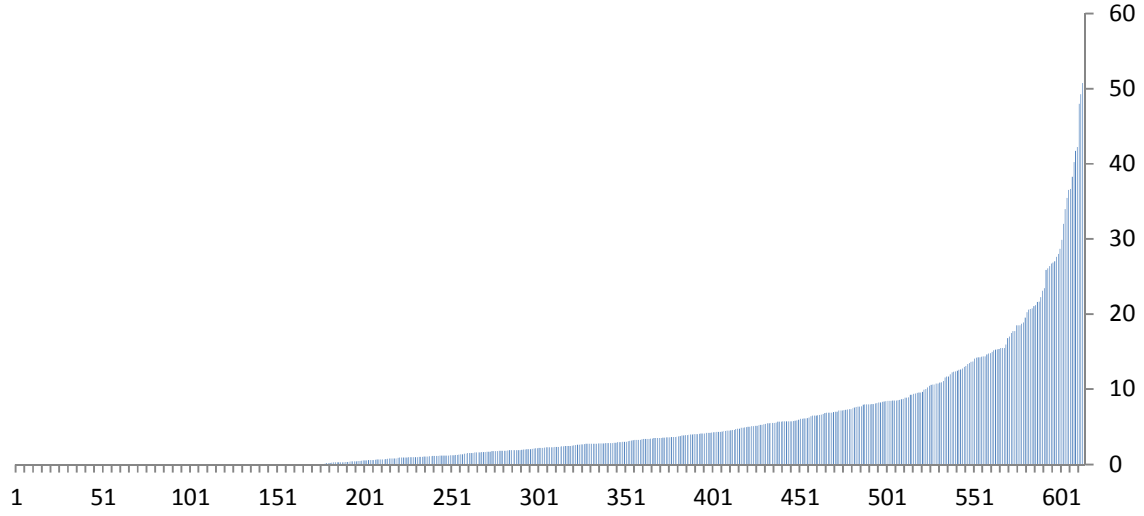


Figure 2: Distribution of deterioration rate for different projects

A comprehensive description of the characteristics of explanatory variables is also as important to better understand the wide range of the hot mix projects included in the analysis. The analysis included both shorter and longer projects ranging from about 1 mile long to 24 mile long with an average length of 4.4 miles. About 50% of the hot mix projects are located in rural areas. The projects are selected for the analysis ensuring a moderate coverage across all the facility types. Dataset included approximately 17% on Interstate Highways, 28% on US highways, 26% on State Highways, 28% on Farm to Market (FM) roads and the remaining being other facility types. Climatic zone of a pavements' location arguably influences the performance of a pavement. In order to effectively account for the weather condition, dataset included about 7% belonging to dry/cold region, 23% belonging to dry/warm region, 31% belonging to wet/warm region and 18% belonging to wet/cold region. Both left and right shoulder width ranged from 'no shoulder category' to about 26 ft and 28ft respectively. Traffic is included in the dataset in three different measures: 1) 18 kip ESAL (Equivalent Single Axle load) count, 2) Annual Average Daily Traffic (AADT), 3) Truck traffic percentage. The dataset included hot mix projects in low, moderate and high traffic regions. The descriptive statistics of the traffic counts are reported in Table 1.

This study is primarily targeted at identifying the relationship between the volumetric properties those are regularly measured during QC/QA and the corresponding project performance. A wide range of volumetric properties ranging from off-target to on-target values is essential to identify the influence of these volumetric properties on performance. Unfortunately, the SM database contains limited projects with off-target volumetric properties and majorly dominated by projects with quality control parameters within the acceptable thresholds of the existing specifications. Researchers acknowledge that the current analysis reports the change in pavement performance due to a change in the quality control parameters being within the existing specification limits. It is important to realize that the current analysis only accounts for sensitivity of these quality parameters to the performance within a narrow range of specification limits. Indeed, it is important to identify such sensitivity for the development of PRS.

Approximately 51% of the hot mix surface projects (those included in the dataset) placed Type-C mix (A typical hot mix for maintenance projects in Texas) and about 43% of the surface projects placed Type-D mix (A typical fine asphalt mix for overlays in Texas); the remaining hot mix projects contained either SMA or Superpave mixes. The ride quality measured immediately after the construction arguably influences the future deterioration. Dataset contained hot mix projects with an initial IRI value varying between 33.8 inch/mile to 191.0 inch/mile with a mean at 80.6 inch/mile. It is trivial to mention that the higher initial ride quality is attributable to the surface roughness of the existing pavement surface before the overlay construction. This reveals the fact that it is important to control for the initial ride quality during any type of performance modeling; it is expected that initial ride quality affects the deterioration rate, which requires empirical evidence though. Descriptive statistics (mean, standard deviation maximum and minimum) are provided for other important QC/QA parameters such as maximum rice density, asphalt content, fineness modulus, dust content, plant density, plant VMA (voids in the mineral aggregate), plant VFA (voids filled with asphalt) and in-place air voids measured using field cores.

Table 1: List of attributes available in the dataset.

	Variable	Mean	Std.Dev.	Min	Max
Performance indicators	Indicator variable: Rutting	0.793	0.405	0	1
	Indicator variable: Longitudinal cracking	0.908	0.289	0	1
	Indicator variable: Alligator cracking	0.814	0.389	0	1
	Indicator variable: Transverse cracking	0.534	0.499	0	1
	Indicator variable: Flushing	0.558	0.497	0	1
	Indicator variable: Raveling	0.179	0.384	0	1
	Deterioration rate (Ride)	5.088	7.883	0	51.875
Project location & traffic information	Project length	4.40	3.97	0.09	24.34
	Project construction year: Before 2005/After 2005	0.254	0.436	0	1
	Project location: Rural/urban	0.508	0.500	0	1
	Facility indicator variable: IH/other	0.169	0.375	0	1
	Facility indicator variable: US/other	0.279	0.449	0	1
	Facility indicator variable: SH/other	0.254	0.436	0	1
	Facility indicator variable: FM/other	0.275	0.447	0	1
	Weather indicator variable: DryCold/Mixed	0.070	0.255	0	1
	Weather indicator variable: DryWarm/Mixed	0.225	0.418	0	1
	Weather indicator variable: WetWarm/Mixed	0.308	0.462	0	1
	Weather indicator variable: WetCold/Mixed	0.182	0.386	0	1
	Shoulder width: right	7.157	2.778	0	26
	Shoulder width: left	6.465	2.853	0	28
	Current 18kip Measured (from PMIS)	29324	38351	113	228079
	AADT Current (from PMIS)	17104	21838	82.5	151091
	Truck AADT percent	15.87	10.50	2.03	69.47
	Speed limit	62.45	8.18	30	80
	Number of through lanes	2.79	1.09	2	6
HMA information & QC/QA parameters	Indicator for Mix type: TYC/Other	0.516	0.500	0	1
	Indicator for Mix type: TYD/Other	0.428	0.495	0	1
	Ride immediately after construction	80.64	24.60	33.77	191.02
	Maximum specific gravity	2.466	0.048	2.325	2.795
	Asphalt content	4.721	0.391	3.542	6.420
	Fineness modulus	1.803	1.263	0.168	6.842
	Dust content	1.018	1.263	0.01	13.57
	Laboratory density	96.10	0.807	91.31	98.67
	Laboratory VMA	14.58	1.22	7.63	19.44
	Laboratory VFA	74.13	3.91	54.49	90.58
	In-place air voids	7.49	1.15	3.72	13.68

5. Model description

As mentioned earlier, the study utilizes various performance indices (dependent variables) and separate model structure was essential for each of these. In general, the performance indicators are categorized into two groups: 1) binary indicator variables (rutting, cracking, flushing and raveling performance indicators), 2) censored continuous variables (deterioration rate). In this section, the following model structures that are suitable for modeling the aforementioned performance indicators are briefly described:

1. Binary probit model
2. Tobit model with endogenous covariates

5.1 Binary probit model:

This study utilizes a binary probit model structure for modeling binary performance indicators. These models involve estimation of a continuous latent variable using available relevant attributes as explanatory variables. Subsequently, this latent variable is split into two segments using zero as threshold value (as shown below). Intuitively, the latent variable represents the latent distress (rutting, cracking, flushing or raveling) magnitude. As mentioned previously, the actual continuous measurement of these distresses (from PMIS) are unreliable. Hence, researchers opted to use binary indicators and to model using the latent variable approach.

$$Y_i = \begin{cases} 1 & if \quad Y_i^* > 0 \\ 0 & if \quad Y_i^* \leq 0 \end{cases} \tag{1}$$

Where,

Y_i is performance indicator of ith project,

Y^*_i is corresponding latent distress magnitude,

The value of the latent distress magnitude Y^*_i is estimated using the following equation:

$$Y^*_i = X_i^T \beta + \epsilon_i \tag{2}$$

Where,

X_i: $[X_{i1}\ X_{i2} \ldots\ldots\ldots\ldots X_{ij} \ldots\ldots\ldots X_{ik}]^T$

$X_{i1}, X_{i2}, \ldots\ldots\ldots\ldots X_{ij} \ldots\ldots\ldots X_{ik}$ are attributes of ith project

β: $[\beta_1\ \beta_2\ \beta_3 \ldots\ldots\ldots \beta_k]^T$

$\beta_1, \beta_2, \beta_3, \ldots\ldots\ldots \beta_k$ are estimated parameters of attributes

ϵ_i: error term with standard normal distribution,

i = 1,…,n where n is the total number of projects included in the dataset.

j = 1….,k where k is the total number of explanatory variables.

The parameters of the explanatory variables are estimated using maximum likelihood approach. The response probabilities are computed using the conditional distribution of y given X under the normality assumption.

$$P(Y_i = 0|X) = P(Y^*_i \leq 0|X) = 1 - \Phi\,(X^T\beta) \tag{3}$$

$$P(Y_i = 1|X) = P(Y^*_i > 0|X) = \Phi(X^T\beta)$$

Where,
Φ : Cumulative distribution function of a normally distributed variable.

The probability of a project showing a sign of distress ($\mathbf{P(Y_i = 1|X)}$) is of primary interest in this model. It is important to note that, the sensitivity of an explanatory variable (such as a QC/QA parameter) is directly proportional (positively related) to the corresponding estimated coefficient.

5.2 Tobit model with endogenous covariates:

Researchers chose a Tobit model structure with endogenous covariates for modeling censored performance indicators (deterioration rate). The model primarily estimates the extent of deterioration conditional on the fact that project has shown some level of deterioration. The use of conditional expectation of the dependent variable is a very useful framework for handling censored and corner solution problems. An ordinary least squares approach is inconsistent for such applications and demands for estimation of the conditional expectation (conditioning on the occurrence of the event and the data).

It is trivial to mention that the error term associated with dependent variable compounds several important attributes that may influence the deterioration rate. For instance, the characteristics of the existing pavement (before the construction) arguably influence the deterioration rate but it is not included in the explanatory variables; thus, it is being compounded into the error term. Unfortunately, the characteristics of the existing pavement govern the initial ride quality to a large extent. Thus, the explanatory variable corresponding to initial ride quality is becoming correlated with the error terms in the model, thereby raising endogeineity concerns. Researchers accounted for such potential endogeneity associated with the explanatory variable corresponding to initial ride quality using instrumental tobit regression approach. The QC/QA parameters are utilized as instruments for estimating the tobit model with endogenous covariates. The model structure is described below in mathematical terms.

$$y_i = \begin{cases} y_i^* & if \quad y_i^* > 0 \\ 0 & if \quad y_i^* \leq 0 \end{cases} \tag{4}$$

Where,
y_i is performance indicator of i^{th} project,
y^*_i is corresponding latent distress magnitude,

The value of the latent distress magnitude y^*_i is estimated using the following equation:

$$y_i^* = y_{2i}\alpha_1 + X_{1i}\beta_1 + \varepsilon_i$$
$$y_{2i} = X_{2i}\beta_2 + \delta_i \tag{5}$$

Where,
X_{1i}: $[X_{1i1}\ X_{1i2} \dots \dots \dots \dots X_{1ij} \dots \dots \dots X_{1ik}]^T$

$X_{1i1}, X_{1i2}, \ldots\ldots\ldots\ldots . X_{1ij} \ldots\ldots\ldots X_{1ik}$ are attributes of ith project

β: $[\beta_1\ \beta_2\ \beta_3\ \ldots\ldots\ldots . \beta_k]^T$

$\beta_1, \beta_2, \beta_3, \ldots\ldots\ldots . \beta_k$ are estimated parameters of attributes

X_{2i}: $[X_{2i1}\ X_{2i2}\ \ldots\ldots\ldots\ldots . X_{2ij}\ \ldots\ldots\ldots X_{2ik}]^T$

$X_{2i1}, X_{2i2}, \ldots\ldots\ldots\ldots . X_{2ij} \ldots\ldots\ldots X_{2ik}$ are instruments of ith project

y_{2i} is the endogenous covariate (initial ride quality)

i = 1,…,n where n is the total number of projects included in the dataset.
j = 1….,k where k is the total number of explanatory variables.
l = 1….,p where p is the total number of instrumental variables.
ϵ_i: Error term with standard normal distribution
δ_i: Error term with standard normal distribution

The parameters of the explanatory variables are estimated using Neweys' two-step estimator for tobit regression. Researchers are interested in knowing the influence of the explanatory variables (such as QC/QA parameters) on the probability of a project to deteriorate and subsequently the extent of deterioration. The following two mathematical quantities are of prime interest.

$$\boldsymbol{P(y_i = 0|X) = P(y^*_i \leq 0|X) = 1 - \Phi\,(X^T\beta)} \quad (6)$$

$$\boldsymbol{E(y|X, y > 0) = X\beta + \sigma\left[\frac{\emptyset\left(\frac{X\beta}{\sigma}\right)}{\Phi\left(\frac{X\beta}{\sigma}\right)}\right]} \quad (7)$$

It is important to note that, the sensitivity of an explanatory variable (such as a QC/QA parameters) is directly proportional (positively related) to the corresponding estimated coefficient.

6. Results and discussion

To reiterate the main objectives, the study primarily focusses on the relationship between the QC/QA parameters and performance indicators. A model that directly relates the QC/QA parameters with performance indicators may not be helpful as it suffers from omitted variable bias. Researchers utilized several attributes that are available from the integrated dataset. A Comprehensive list of explanatory variables that are currently included in the analysis is shown in Table 1. Although, the estimation procedures are different for the two model structures mentioned in the previous section, specification refinement is quite similar. Firstly, an unrestricted version of the specification is initially formulated including most intuitive attributes. Subsequently, statistically insignificant variables are dropped from the specification in order to refine the model. Intuition played a leading role in removing and adding the attributes rather than solely depending on the statistical tests during such refinement process. The specification refinement is carried out using typical statistical test procedures such as F-test and Likelihood Ratio (LR) test to develop final restricted and refined specifications.

As mentioned previously, seven performance indicators are available in the integrated database; as a result, seven different specifications have been developed. However this paper reports only three of them; the remaining four models are of no interest to the researchers considering the statistically weak relationship between most of the attributes and the respective performance indicators. A detailed description of the estimation results with respect to the following three performance indicators is provided below: 1) rutting 2) transverse cracking and 3) deterioration rate. A thorough understanding of both magnitude and sign of the statically significant estimated coefficients is essential to get a deeper insight into the relationship between the performance indicators and the most relevant attributes. The following sections provide the intuition behind the estimated coefficient magnitudes and their signs.

6.1 Deterioration rate

This model utilizes the censored deterioration rate as performance indicator (dependent variable). At this point, researchers intend to reemphasize on the fact that the presented model is not a typical pavement deterioration model which predicts pavement condition at a certain time; rather it relates an aggregated performance measure over a period of three years to the attributes of interest (for e.g. QC/QA parameters). As mentioned previously, a Tobit type specification with endogenous covariates is utilized for developing the deterioration rate model. The volumetric properties measured during QC/QA are utilized as instruments; in other words, it is assumed that they indirectly influence the deterioration rate through their influence on initial ride quality. The estimation results are reported in Table 2. It is to be noted that, only second stage estimates are reported in this memorandum; the first stage estimates corresponding to instrumental variables is regarded unimportant for the discussion.

Firstly, initial ride quality measurement immediately after the construction is observed to be statistically significant with a positive coefficient. This is an important finding; this underscores the importance of controlling ride quality immediately after the construction during the QC/QA and justifies incorporating it into pay adjustment scheme. Intuitively, a pavement with a larger initial ride quality is expected to deteriorate faster while keeping the other factors unchanged; the positive sign is supporting this hypothesis. Researchers encourage utilizing the ride quality measurement for pay adjustment as it is directly associated with the deterioration rate during the first three year period. Secondly, a negative sign on the indicator variable corresponding to Interstate Highways suggests that Interstates are deteriorating at a slower rate relative to the other facilities while controlling for the other factors influencing the deterioration rate, which is expected. This specific finding also encourage for developing individual pay adjustment schedules for different facilities. Thirdly, the coefficient corresponding to right shoulder width is suggesting that larger shoulder widths beside the lanes carrying slower and heavier traffic is not adding any value to the performance. Researchers are hesitant to discourage the construction of the wider right shoulders. The finding is not supported by the intuition; as mentioned previously, it is precarious to rely solely on statistical significance. A possible explanation for the behavior could be as follows: the shoulder can be thought of a proxy variable for local soil condition at the project location. In general, wider shoulders are provided for pavements with weaker subbase and thus explaining the positive sign on the estimated coefficient.

Table 2: Estimation results: Deterioration rate

Variable	Estimate	Std.Dev.	Z-Score	P-value
Constant	-16.967	0.377	-1.88	0.059
Indicator variable: Interstate Highway	-5.031	0.468	-2.17	0.030
Right Shoulder Width	0.454	0.155	2.12	0.034
Ride at the time of construction (IRI in inch/mile)	0.222	0.416	2.10	0.036

Instruments: Maximum specific gravity, asphalt content, fineness modulus, filler content, in-place air voids, laboratory density, laboratory VFA, laboratory VMA, TYC, TYD, weather
Test of exogeneity: P-Value: 0.0173

6.2 Rutting

This model utilizes binary rutting related performance indicator as dependent variable. The statistically significant binary probit model estimates are reported in Table 3. A detailed description of both magnitude and coefficient of these estimated coefficients is provided below. It is to be noted that, these coefficient reveal the influence of the corresponding attribute on the probability of a project to exhibit any sign of rutting during the first three year period immediately after the construction.

Table 3: Estimation results: Rutting

Variable	Estimate	Std.Dev.	Z-Score	P-value
Constant	1.057	0.074	14.255	0.00
Length of the project	0.081	0.022	3.749	0.00
Current 18-Kip measured average	-0.085	0.033	-2.562	0.011
Constructed before 2005	-1.099	0.139	-5.125	0.00
Indicator Variable: Wet-Warm Weather	-0.713	0.148	-7.409	0.00
Speed Limit	0.291	0.086	3.389	0.001
Indicator Variable: Rural	-0.355	0.145	-2.452	0.015
Laboratory VFA	0.318	0.166	1.917	0.056

Firstly, the estimated coefficient corresponding to VFA (voids in the filled asphalt) is indicating that the laboratory VFA is positively related to the probability of a project to show early signs of rutting. It is to be noted that none of the other plant measured volumetric properties are statically associated with the performance (specifically rutting). This is an important finding suggesting that pay adjustment based on VFA is better justified from the performance perspective; currently TxDOT used laboratory density for pay adjustment. In addition, magnitude of the project, traffic, weather, speed limit and project location are associated with the probability of a project to exhibit any signs of rutting in first three years. The findings suggest the importance of controlling traffic and weather during mix design as they are directly associated with early

rutting performance of hot mix projects; TxDOT currently does not account for the weather and traffic for mix design.

6.3 Transverse cracking

This model utilizes binary transverse cracking related performance indicator as the dependent variables. The statistically significant binary probit model estimates are reported in Table 4. A detailed description of both magnitude and coefficient of these estimated coefficients is provided below. It is to be noted that, these coefficient reveal the influence of the corresponding attribute on the probability of a project to exhibit any sign of transverse cracking during the first three year period immediately after the construction.

Table 4: Estimation results: Transverse cracking

Variable	Estimate	Std.Dev.	Z-Score	P-value
Constant	0.103	0.054	1.908	0.057
Length of the project	0.063	0.015	4.077	0.000
Indicator Variable: Dry-Warm Weather	0.328	0.139	2.368	0.018
Indicator Variable: Wet-Warm Weather	0.360	0.128	2.817	0.005
Indicator Variable: FM facility	-0.647	0.126	-5.150	0.000
Truck AADT percentage	0.163	0.061	2.654	0.008
Indicator Variable: Rural	-0.351	0.120	-2.936	0.003
Ride quality immediately after the construction	0.064	0.023	2.733	0.006

Firstly, the coefficient corresponding to ride quality immediately after the construction is statistically significant or associated with the probability of a project to show any early signs of transverse cracking. Intuitively, a pavement with a higher initial roughness is expected to produce any form of structure related distress because of increased impact loading activity; thus, a positive sign is justifiable. Secondly, data suggests that the weather and rural location has a statistically significant association with the probability of a project to exhibit any early signs of transverse cracking. It is interesting to observe a positive sign on the coefficient corresponding to truck traffic percentage, which is expected.

7. Summary and preliminary conclusions

This paper presents an empirical approach to develop relationship between routinely measured QC/QA parameters and corresponding pavement performance. The methodology primarily emphasizes on utilizing field data for developing performance based specifications. Researchers utilized early performance behavior of newly constructed hot mix pavement behavior rather than modeling the long term performance. The performance data from a three year period immediately after the construction is aggregated to develop a total of seven types of performance

indicators in terms of the following distresses; Ride quality deterioration, rutting, transverse cracking, alligator cracking, longitudinal cracking, flushing, raveling. Two statistical modeling frame works are adopted for handling the different formats of performance indicators (binary and censored): 1) Binary Probit, 2) Tobit with endogenous covariates. The estimated results are presented and discussed in detail.

Data suggests that ride quality immediately after the construction is associated with both deterioration rate and probability of a project exhibiting early signs of transverse cracking within first three years. It is also statically evident that the influence of the initial ride quality is different for Interstate Highways. Additionally, rutting model revealed that Voids in the Filled Asphalt (VFA) is associated with the probability of a project to exhibit early signs of rutting. Data also suggests that laboratory density (which is currently part of the pay adjustment system) is not associated with any of the performance indicators. Although not specifically reported, in-place density was found to be weakly associated (at 10% level of significance) with alligator cracking; the strength of relationship is expected to increase with the increase in number of records (or projects). It is interesting note a negative correlation between the in-place density and the probability of a project to exhibit any early signs of alligator cracking.

The study team is currently updating the model findings with newly available performance data at TxDOT. An updated model specification developed using the new dataset (more number of records) will be reported along with the sensitivity analysis results. Subsequently, research team will publish the performance related measurable quality control parameters along with their sensitivities. Finally, a recommendation will be made on performance based pay adjustment scheme for Texas.

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