A Framework for Modeling Pavement Distress & Performance Interactions

Developing a usable framework requires determining to what extent the various pavement characteristics influence the process of road surface deterioration.

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Although a precise relationship between pavement distress and performance has not been definitively established, there is a consensus that the ability of a pavement to withstand traffic loads and serve the motoring public in a safe and efficient manner is adversely affected by observable surface distress. This distress, if untreated, ultimately becomes manifested as roughness, which interferes with proper surface drainage, causing water ponding on the surface, which in turn leads to negative impacts on the performance of the pavement and on vehicle safety. A review of research efforts also indicates that relatively little systematic modeling has been done to examine the interrelationship between distress and pavement performance despite its crucial importance.

Overview

The aging road infrastructure in the United States — coupled with the increasing pressure for governmental fiscal austerity and increasing demands for improved management and planning techniques — exemplifies to varying degrees the problems facing highway planners, financiers and engineers at national, state and local levels. At the core of addressing these problems is the need to assess the current and future condition of the highway network. This assessment, together with a coherent policy and set of maintenance standards, would aid in determining the level of service to be provided as well as in determining the funding required to support that level of service. Consequently, predicting pavement distress and performance has become the focus of many research studies in recent years as highway agencies acknowledge the need to upgrade their pavement management systems (PMS).[1]

A report on the feasibility of a PMS for the State of Connecticut identified the need to develop pavement performance prediction models that could be used for network-level budget optimization. Pursuant to this need, a long-term monitoring (LTM) program was initiated in 1984 by the Connecticut Department of Transportation (ConnDOT). The purpose of this 10-year study of in-service pavements with varying characteristics was to gather pertinent data in the form of pavement distress, skid resistance, roughness and maintenance history for 82 LTM sites. These sites consisted of 57 flexible, 11 rigid and 14 composite pavements. The flexible pavements were broken into three subcategories:

- Thirty-three sites that had overlays on liquid-treated pavements;
- Fourteen sites that had overlays on the original flexible pavement; and,
- Ten original flexible pavements having no overlays.

It was possible to develop a conceptual framework and analysis based on the data collected by ConnDOT between 1984 and 1989 on the 14 sites containing overlays on original full-depth pavements. The purpose of this analysis was two-fold:

- To develop and test a framework for modeling pavement distress and performance interactions; and,
- To identify areas needing improvement in the ConnDOT database system prior to developing more comprehensive performance models at the end of the LTM project.

The framework proposed herein uses pavement roughness (a quantitative measure of road surface distortions that result in an uncomfortable ride for the motorist) over time as a direct quantitative measure of performance, rather than a combined index such as the Present Serviceability Index (PSI). The use of roughness is based on results of several studies that concluded, in many instances, that roughness measurements alone may be sufficient in predicting pavement serviceability.[2-4] If a significant relationship does exist between distress and roughness, then a one-time expenditure on roughness measurement equipment may be all that a highway agency requires to determine road conditions and to monitor road performance. In that way, the agency can cut costs on extra equipment and other activities involved in the direct measurement of distress.

Studies have also shown that the cost of operating vehicles increases with pavement roughness. Therefore, the existence of a significant relationship between roughness and distress could provide a method to determine the relationship between distress and vehicle operating cost. At the local level, engineers are more familiar with the concept of distress rather than that of roughness.[5] Therefore, if the latter relationship (vehicle operating cost versus distress) is developed, it could provide a sound basis for engineers (particularly at the local level) in formulating their annual or periodic pavement maintenance needs that are presented before town budget committees.

A workable model should address the following questions:

- To what extent do various characteristics of a pavement — mix design properties, past distress levels, age, the environment (as represented by pavement regional location) and maintenance history (including the quantity of sealed cracks and the corresponding age of the crack sealants) — influence deterioration?
- Since cracking is the predominant distress that was observed on LTM sites in Connecticut, could it be used to represent all road surface distress?

Framework Development

General Concepts of Pavement Deterioration. The concept of pavement deterioration has been well documented by Paterson.[4] The mechanism of pavement deterioration is related to the physical or mechanical behavior of the pavement and its various components. Weather and traffic factors influence pavement deterioration. Repeated axle loadings induce various stresses and strains within pavement layers, resulting primarily in cracking. The combined action of weathering and oxidation also causes bituminous surfaces to become brittle and, hence, more susceptible to cracking and disintegration, especially if the quality of the mix design and construction work were low. Once initiated, cracking levels (in terms of severity and extent) increase to a point where spalling occurs and potholes often develop. Open cracks on the surface and poorly designed and maintained drainage systems permit excess water to penetrate the pavement. This seepage accelerates the process of disintegration and reduces the shear strength of the subgrade and/or the subbase. These cumulative deformations throughout the pavement result in ruts in the wheel paths and in surface roughness.

The roughness of a pavement is, therefore, the result of a chain of distress mechanisms involving the combination of various modes of distress. A proper maintenance program can usually reduce the rate of deterioration, but certain forms of maintenance, such as patching, may increase roughness slightly. Roughness is thus viewed as a composite distress — comprising components of deformation due to traffic loading and rut depth variation, surface defects from spalled cracking, potholes, patching, and a combination of aging and environmental effects.

Distress & Performance. The concept of performance as a measure of highway deterioration has been widely analyzed and discussed by many researchers.[4,6-9] A combined index such as the PSI is a popular pavement performance analysis tool. Recent modeling techniques, however, are shifting from the combined index approach to a more objective measure such as pavement roughness. These techniques also adopt a more versatile approach in which major distress modes are individually modeled to better analyze and explain the relationship between distress and performance.

Pavement performance is usually defined as the variation in the level of service, or serviceability, provided to the pavement user over time. Distress, on the other hand, is a form of limiting pavement behavior characterized by perceptible evidence of physical deterioration.[10] Prediction models for performance can have either a probabilistic or deterministic basis.

Probabilistic models have utilized Markov's theory and have often been considered desirable because of their ability to recognize and accommodate uncertainty.[11] In spite of the elegant theory or structure of the Markov chain models, there is the problem of how to develop a transition matrix. The Markov process also depends only on the present state in predicting the future state. However, various studies have shown that other variables such as loading and age of pavement are also significant in predicting a future state. Markov-based models assume that transition probabilities are constant over time; *i.e.*, the Markov chain is assumed to be homogeneous. Since traffic loads generally increase over time, and maintenance methods also vary over time, this assumption may be unrealistic.

Deterministic analyses, as found in the literature, are based on functional performance (which relates objectively measured pavement behavior to the average user's opinion of serviceability), structural performance and damage assessment. For structural performance, features such as cracking, rutting and raveling are used to measure the physical condition of the pavement. Damage is typically quantified as a number ranging from 0 to 1. Typically calibrated using regression techniques, the deterministic model may be either based on empirical or mechanistic empirical correlations.

The use of roughness as the primary measure of performance (*i.e.*, serviceability over time rather than a combined index such as PSI) seems more useful since the user's perception is dominated by riding comfort, which is usually estimated by roughness.[3] Hence, by relating roughness to different combinations of various amounts of distress measured during a pavement's life, the serviceability-age profile or performance of a pavement can be realistically related to distress.

As outlined by Paterson, there are also major problems with using a summary statistic such as PSI as a performance parameter:[4]

- Different types of maintenance are appropriate for different levels of each distress type.
- The relative seriousness of different defects varies with the pavement type, envi-

ronment, the rate of deterioration and the maintenance program. (For example, the relative weightings developed for asphalt pavements in the wet-freezing climate of the Illinois region as a result of the AASHO Road Test are not necessarily applicable to pavements with thin surfacings or composite pavements, nor are they suited to pavements in a dry nonfreezing climate.)

- Each distress type evolves at different rates in different pavement types and under different traffic and environmental conditions.

Thus, modeling the performance by using PSI alone requires determining the average amount of distress from the many different combinations of these types of distress. This method could yield results that have wide variances that, in turn, may suppress the very effects that are of interest.

Framework Assumptions. Based on the preceding discussion, the following concepts serve as the assumptions that can be employed in developing a model for relating pavement performance and distress:

- The future characteristics of a pavement depend on how those characteristics have performed in the past (*i.e.*, pavement characteristics are recursive in form). Hence, the level or amount of a specific type of distress has a direct relationship to the level or amount of distress that was last observed.
- Pavement aging leads to increasing amounts of distress.
- The amount of distress observed depends on the previous traffic levels (expressed in terms of equivalent single-axle loadings).
- The amount of distress observed depends on the maintenance history of the pavement (for example, pavement age as well as the quantity of sealed cracks).
- Cracking may be used as a surrogate for all distresses in representing road surface roughness (since it was the most significant observed distress on LTM sites in Connecticut).

The framework that is depicted in Figure 1 illustrates the complex relationships that exist among pavement deterioration factors (or inputs), the deterioration process, serviceability and performance. Models for various distress types — for example, cracking or rutting — represent the deterioration process. These models use the deterioration factors — such as weather, loading, or construction and maintenance practices — as inputs to predict distress. For this framework, pavement roughness is considered to be the primary indication of distress. Thus, roughness is viewed in terms of the road surface distortions that contribute to an undesirable or uncomfortable ride.

Rough pavements, when untreated, generate increased dynamic loads that hasten the deterioration process. This relationship suggests that beyond a certain level of distress, there is a two-way causation between roughness and distress. However, since cracking was the only form of distress employed in this framework, the impact of increased dynamic loading was assumed to be insignificant. If far greater levels of other types of distress such as potholes and corrugations were encountered, modifications would certainly have to be made to the framework. Some forms of maintenance (for example, patching) may increase roughness slightly even though these practices are intended to reduce pavement deterioration. Over time and/or usage, the serviceability-time or usage profile portrays the general performance of the pavement.

Framework Examination

Using the set of assumptions presented earlier, pertinent data were required to examine the efficacy of the framework shown in Figure 1. The database used for this task included a time series data set on 14 segments of flexible pavements gathered between 1984 and 1989 by ConnDOT as part of its long-term pavement monitoring study. The database consisted of the average annual daily traffic (AADT), pavement cross section, core characteristics, pavement age since the last overlay, South Dakota Road Profiler roughness measurements, sealed and open cracking, patching, skid resistance and environmental information (as repre-

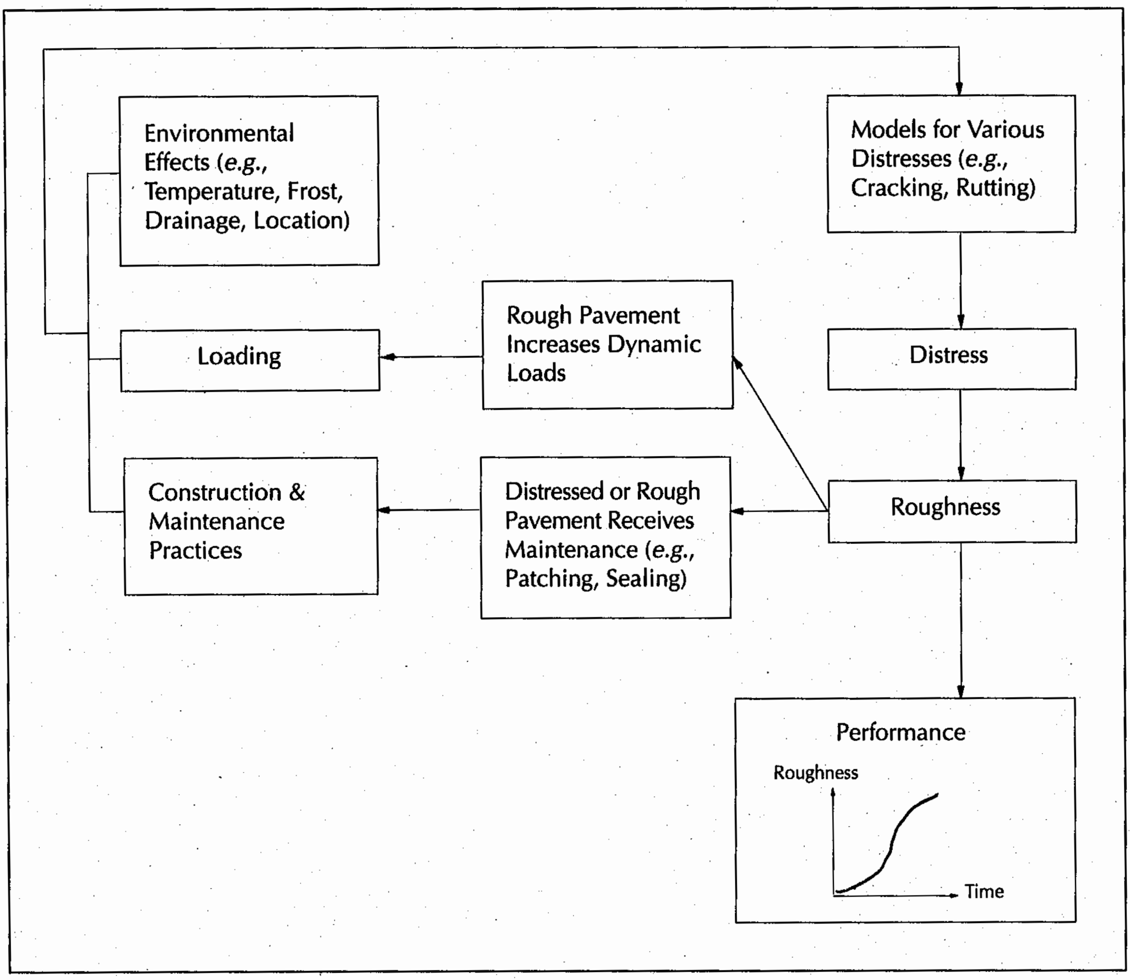

FIGURE 1. A framework for relating pavement distress to performance.

sented by pavement regional location). The main focus of this study was on cracking, since significant amounts of other types of distress were not encountered on the ConnDOT LTM sites. Each of the 14 segments was 1,000 feet long and contained overlays on the original flexible pavements. The age of these overlays ranged in age from three to 15 years.

Data Analysis

Analysis of the data consisted of two phases: a preliminary phase and a model-building phase. The former used cross classification, correlation and regression analyses techniques to select key variables for the model-building phase. Additional regression analyses techniques were performed during the model-building phase on the variables that were assumed to influence pavement deterioration.

The first step involved in the preliminary analysis was to compute for each pavement the structural numbers from the core information, the equivalent single-axle loadings (ESAL) from the AADT data and extract from maintenance records the amount of sealed cracks (as well as the corresponding age of the seal at any time within the observation period).

The next step was to subject the entire data set to further analysis using cross classification, scatter plots and correlation techniques. A series of regular and non-linear regression analyses was then performed to examine whether significant relationships existed among the variables. A fundamental assumption was

TABLE 1.
Variables & Functions for Regression Results

LC_t = Open longitudinal cracking in year t (ft/100ft)
TC_t = Open transverse cracking in year t (ft/100ft)
$TOTC_t$ = Combined or total cracking in year t (ft/100ft)
RN_t = Roughness in year t (inch/mile)
TS_t = Sealed transverse cracking remaining in year t (ft/100ft)
$TOTS_t$ = Combined or total sealed cracking remaining in year t (ft/100ft)
PAGE = Pavement age since the last overlay (years)
R^2 = Coefficient of determination
SAGE = Age of sealed cracks (years)
SN = Pavement structural number
VTYP = Dummy variable for equipment used for roughness measurements

General Functions for Dependent Variables — Pavements With Sealing History

$TOTS_t = f(PAGE, SAGE)$
$TOTC_t = f(TOTC_{t-1}, PAGE, SN, TOTS_{t-1}, SAGE)$
$TS_t = f(PAGE, SAGE)$
$TC_t = f(TC_{t-1}, PAGE, SN, TS_{t-1}, SAGE)$
$LC_t = f(LC_{t-1}, PAGE, SN, SAGE)$
$RN_t = f(RN_{t-1}, SAGE, TOTC_t)$
$RN_t = f(RN_{t-1}, SAGE, TC_t, LC_t)$

General Functions for Dependent Variables — Pavements Without Sealing History

$TOTC_t = f(TOTC_{t-1})$
$TC_t = f(TC_{t-1})$
$LC_t = f(LC_{t-1}, ESAL_{t-1}, PAGE)$
$RN_t = f(VTYP, SN, RN_{t-1})$

made that maintenance, in the form of crack sealing, can retard pavement deterioration. Therefore, stratification of the data during classification analysis was necessary so that trends could be observed separately for segments with and without crack sealing history. (The term *history* is used here to mean whether sealing has been done on the pavement in previous years.)

The correlation analysis step involved selecting the appropriate form of the variables that could be used to explain the relationships among traffic, the environment, distress and serviceability (as measured in terms of roughness at a specific time). A correlation matrix was set up to determine whether there was a relationship between pairs of variables. A test of this proposition involved examining the data to find out if they support such a proposition. This matrix was employed to examine the strength of association between a dependent variable and an independent variable.

While a correlation analysis provides an assessment of the strength of the relationships among the variables, a regression analysis on the other hand permits drawing conclusions about the functional relationships existing among the variables. The regression analysis option of the statistical analysis software (SAS) employed in the analysis was used to perform all analyses pertaining to regression. The SAS regression analysis option was performed only for cases with no missing data for any of the variables selected for analysis. The regression equations were evaluated using the following criteria:

- Test of significance of regression (F-test) to assess the overall significance of fitting the regression equation.
- Test of significance of each variable (t-test) to determine how important any one term is in the regression equation after all other terms have been included.

Framework Model Building

The model-building phase for the proposed framework consisted of selecting the key variables that could be used to explain the mechanism of distress formation and the interaction between distress, performance, traffic and the environment (a dummy variable represented by pavement regional location). The pave-

TABLE 2.
Model Parameters for Pavements That Have Not Experienced Any Crack Sealing

Dependent Variable	Independent Variable	Variable Coefficient	t-Value	Constant Term	Variable Exponent	Model R^2
$TOTC_t$	$TOTC_{t-1}$	1.28	20.61	—	—	0.953
TC_t	TC_{t-1}	1.10	25.34	—	—	0.968
LC_t	LC_{t-1}	1.13	8.08	—	—	0.953
	$ESAL_{t-1}$	5.16×10^{-5}	2.15			
RN_t	RN_{t-1}	1.10	2.40	—	0.75	0.837
	SN	54.09	2.31		-2.00	

ments under study fell within three regional locations: the shoreline area close to Long Island Sound, the Connecticut River valley, and a hilly area (which tends to have a much cooler climate compared to the other two locations).

The dependent variables for each of the two broad categories (cracks with and without a sealing history) included: roughness, transverse cracking, longitudinal cracking and combined cracking (which is the sum of all cracking forms observed, predominantly longitudinal and transverse cracking with very few cases — less than one percent — of alligator cracking). The independent variables that would explain the variation were selected based on the results of the correlation and regression analyses. The only environmental variable considered in the regression analyses — *i.e.,* the pavement regional location — was not statistically significant and, therefore, was dropped from further consideration. The selected variables are defined in Table 1.

Using the generalized functional forms also presented in Table 1, the final values obtained as a result of further regression analyses are summarized in Tables 2 and 3. (A variable appearing with subscript *t-1* denotes the quantity of the variable in the previous year.) Only independent variables that were statistically significant were included in the final results. The

TABLE 3.
Model Parameters for Pavements That Have Experienced Crack Sealing

Dependent Variable	Independent Variable	Variable Coefficient	t-Value	Constant Term	Variable Exponent	Model R^2
Log_eTOTS_t	PSAGE*	-0.04	-3.85	3.52	—	0.220
Log_eTS_t	PSAGE	-0.04	-5.31	2.99	—	0.357
$TOTC_t$	TOTCS**	0.66	9.88	—	0.10	0.921
	PSAGE	98.14	4.16			
	SN	-34.79	-4.73			
TC_t	TSCT***	0.53	6.43	—	0.10	0.918
	PSAGE	24.33	3.38			
	SN	-7.96	-3.79			
LC_t	LCB§	1.16	8.80	—	—	0.903
	PSAGE	47.07	4.52			
	SN	-14.56	-3.88			
$Log_{10}RN_t$	$Log10RN_{t-1}$	0.52	4.37	0.5	—	0.546
	$Log_{10}SAGE$	0.41	2.96			

* PSAGE = PAGE × SAGE
** $TOTCS = TOTC_{t-1} - 186.21/(TOTS_{t-1})^{0.23}$
*** $TSTC = 6.93 \times (TC_{t-1})^{0.51} + 60.26/(TS_{t-1})^{0.24}$
§ $LCB = 6.92 \times (LC_{t-1})^{0.56}$

TABLE 4.
Summary of Actual & Predicted Cracking & Roughness Data for 1990

LTM Site	Longitudinal Cracking			Transverse Cracking			Total Cracking			Roughness		
	Actual	Predicted	Error (%)	Actual	Predicted	Error (%)	Actual	Predicted	Error (%)	Actual	Predicted	Error (%)
F1	105	90	14	61	42	31	166	119	28	28.8	12.4	57
F2	160	132	18	66	49	26	382	326	15	8.3	14.3	72
F3	41	87	111	56	59	5	217	156	28	23.1	31.0	34
F4	102	121	18	33	35	6	243	136	43	12.4	23.7	91
F5	11	45	303	14	37	158	25	87	248	2.1	19.6	833
F6	141	126	11	52	39	25	193	154	20	3.6	10.5	192
F7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
F8	228	116	49	34	60	76	262	162	38	42.5	29.0	32
F9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
F10	NA	NA	NA	1	2	100	1	2	100	4.2	7.2	71
F11	43	77	79	27	44	63	70	113	61	27.7	38.5	39
F12	65	77	18	83	57	31	148	143	3	14.6	41.4	184
F13	154	136	12	54	52	4	208	190	9	36.6	41.3	13
F14	160	216	35	55	61	11	215	276	28	12.5	10.1	19
Mean*			37			26			27			73
Number of Observ.		10			11			11			11	

*Mean prediction errors computed excludes LTM site F5.

results in Tables 2 and 3 indicate that future cracking levels are highly dependent on past cracking levels regardless whether the pavement has received crack sealing or not. Table 2 further indicates that for flexible pavements that have not received any form of crack sealing, the previous cracking levels alone may be sufficient in predicting future cracking levels. This conclusion is supported by the high R^2 values associated with the results from the various cracking forms.

Framework Model Testing

The robustness of the model that was developed was tested by predicting the 1990 characteristics for the LTM sites. The 1990 data were not part of the data set used for the model calibration. Table 4 shows a summary of the 1990 actual and predicted cracking and roughness data for the 14 sites. Characteristics for sites F10 and F14 were predicted using the model for pavements without a crack sealing history. Those sites with a crack sealing history (with the exception of F9) were predicted using the model for pavements with a crack sealing history. In Table 4 the predicted values were rounded to whole numbers; however, errors associated with prediction were computed based on the as-predicted values. Table 4 also presents predictions for only 12 out of the 14 sites since descrepancies existed in the 1990 data for sites F7 and F9.

It can be seen from the data in Table 4 that a majority of the errors associated with the predicted roughness values are extremely high. The mean error of roughness prediction is approximately 73 percent (not including site F5). This number goes up to 136 percent if site F5 is included (which makes the model less attractive). Consider the three sites with roughness prediction errors greater than 100 percent: sites F5, F6 and F12. Their respective 1989 roughness values were 14.1, 4.2 and 34.2 inch/mile, respectively. The expected trend for 1990 was that, without any major improvements, these numbers should have been at least equal to their previous values. However, the actual 1990 values (see Table 4) were much lower than expected. The large errors in the roughness category might be due to such factors as the inability of driver to drive in the previous year's wheel paths or errors in the devices used to measure the roughness values. The mean predicted error ranged from 26 percent for transverse cracking to 37 percent for longitudinal cracking (both excluding site F5).

Limitations

The limitations of this type of analysis may stem from data acquisition problems rather than from any conceptual flaws. The development of an appropriate prediction model for pavement network optimization would depend to a large degree on the reliability of the acquired data. Data reliability is important and cannot be overlooked in subsequent statistical analysis.

A significant limitation faced in this study was the unavailability of adequate traffic loading data for a majority of the road segments. Therefore, these data had to be estimated using AADT and the assumed growth rates for various truck types. The assumed growth rates were obtained from other road segments that were believed to have similar characteristics. It was expected that traffic loading would create a positive impact on levels of cracking and pavement roughness, but this was not the case. The element of loading could, therefore, not be adequately represented in the final models.

The preliminary analysis indicated that there was an extremely weak relationship between roughness (a dependent variable) and cracking and the type of vehicle used to make the roughness measurement (independent variables) compared to other independent variables such as the age of the crack sealants and the pavement structural number. This anomaly could be due to a number of factors:

1. Distress ratings on the ConnDOT LTM sites were conducted on a specific 100-foot sample unit within a 1,000-foot road segment. A summary of the roughness values corresponding to the 100-foot sample unit was unavailable at the time of the study, but it was nevertheless decided to attempt to correlate roughness with cracking.

2. In 1984 ConnDOT made special runs on LTM sites to obtain roughness values and to precisely demarcate start and end points. However, beginning in 1985, all roughness data were obtained using computer files for normal photolog inventories. (A photolog inventory is conducted using a special type of van equipped with facilities to collect photographic images of the roadway and roughness measurements from an axle-mounted accelerometer.) It is suspected that since 1985 there could be deviations of up to 0.03 mile between the position of the vehicle and the actual log mileage. This discrepancy suggests that the roughness summary may not completely cover the actual test segment.

3. A number of characteristics for the roughness measurement vehicles have changed over the years. For example, between 1984 and 1986, the measurement vans had a tire and a wheel size of 19 inches. This dimension was reduced to 16.5 inches beginning in 1987 when radial tires were mounted. Even though ConnDOT used the same van for roughness measurements, each year certain maintenance procedures could produce variations outside the normal expected trend. ConnDOT readjusted the vans for each test season using potentiometers. The vans were driven over a couple of roads and not over the same set of calibration bumps. These vans and accompanying equipment then were readjusted on the basis of potentiometer output that may be widely different from the previous year's.

4. Reliable data depends on the ability of the driver of the van to repeat the previous year's lateral path through the test site. This practice ensures that roughness measurements are made over the same spots each year. However, it is a difficult task even for the same driver to take the exact same path through a road segment. If the driver of the van varies each test season, the lateral path will most certainly vary.

5. The components of the vehicle may degrade over time. Shocks, springs and tires wear and are replaced. Equipment failures require the repair and replacement of circuit boards and electronic devices.

6. Even if data acquisition procedures for all other variables could be held constant, site condition data can still vary if a wide range of posted speed limits exists for these segments. Roughness has been found to be speed dependent for response-type roughness measuring devices. Therefore, two segments of "similar" surface characteristics, for example, would be likely to have different roughness values due to differences in posted speed limits.

The model testing results indicated that cracking predictions for some sites, particularly F5, were two to four times higher than the cracks actually observed. These divergences make the model less attractive. However, this seeming unreliability could be due to the fact that the 1990 data were collected by a survey crew that was different from the usual crew that had performed the survey for the past six years. Even though standard procedures existed for conducting the survey, measurement errors might have occurred because of unfamiliarity with proper measurement methods.

Conclusions & Recommendations

In developing this conceptual framework for relating pavement distress to performance, pavement roughness over time was used as a direct quantitative measure of performance. This approach was based on the results of a number of studies. Since distress ultimately manifests itself as pavement surface roughness, the framework suggests that to better understand the interrelationship between distress and performance, various types of distress should be modeled as independent modes of distress and then their relationship with roughness examined.

The proposed framework was tested using data from 14 pavement segments located in Connecticut. Various forms of cracking — including predominantly longitudinal and transverse cracking, with less than one percent alligator cracking — comprised the only type of distress that was modeled in testing the framework since it was the only significant visible distress occurring on the highway pavements monitored.

Based on the results of this study, the data do not adequately support the contention of a relationship between cracking and roughness. The suitability of the proposed framework could, therefore, not be fully assessed primarily because of data limitations. Further investigation is recommended. The data, however, support the following observations:

- The progression of cracking is primarily a function of previous cracking levels for pavements that have experienced some form of sealing (see Table 3). In addition, the previous level of cracking alone may be sufficient for predicting the future cracking for pavements that have experienced no sealing in the past (see Table 2). The future roughness of a pavement is also found to be primarily dependent on its current and past roughness (see Tables 2 and 3). These observations, therefore, do support the hypothesis that the future characteristics of a pavement depend on the history of those same characteristics.
- Although it is widely claimed that the age of a pavement will have a significant impact on deterioration, this analysis shows that the age alone may not be treated in isolation for pavements with a crack sealing history, because it is the interaction between the pavement age and the age of sealed cracks that influences deterioration.

The following recommendations regarding data collection and analysis should be considered for future modeling of pavement behavior:

- Having to adjust roughness measurements to posted speed limits suggests that segments with the "same" surface characteristics are likely to have different roughness values due to differences in posted speeds. For such situations, maintenance decisions based on roughness data are likely to trigger a wide range of maintenance actions that could be uneconomical. Therefore, it would be advisable to develop procedures for measuring roughness at some standard speed and restrict applying it to situations where obscure pavement geometrics, pedestrian and vehicular traffic would make it impossible to operate at the standard speed.

- As far as cracking is concerned, the mechanisms that induce roughness are the effects of spalling and unevenness generated across cracked blocks of surfaces and the birdbath-type depressions that often result from localized deformation in the base as a result of surface cracking. Hence, for a more objective examination of the relationship between cracking and roughness, it might be useful to consider only medium to severe cracking in future modeling regarding the relationship between the two variables.
- The process of collecting distress data based on the definition of the term *cracking* as the combination of open and sealed cracks should be abandoned. Sealed cracks are assumed to prevent water from penetrating the pavement, consequently retarding the deterioration process. Therefore, to model cracking it is recommended that the term *cracking* be redefined to differentiate among open and sealed cracks. However, if the combined definition is adhered to, then future modeling of cracking should incorporate a separate model for sealed cracks, which can be used to extract the amount of sealed cracking embedded in the combined model.
- Further preliminary results of the ConnDOT study indicate that there is a positive relationship between cracking and roughness. However, the results of the significance tests suggest that this relationship is extremely weak. Therefore, the central question of whether cracking can be used as a surrogate for all distress in representing roughness cannot be definitively answered based on the results of this research. Further investigation is required. ConnDOT could extract from its mileage records summaries of roughness data corresponding to the 100-foot units over which distress was rated. These data might provide a better basis to examine this relationship.
- Longitudinal and transverse cracking formed the predominant type of distress analyzed in this study. Both types of cracking result from an environmental fatigue process that is determined largely by material characteristics and the temperature regime. It would make better sense to employ pavement temperature as a more specific environmental variable in future modeling of these cracking types rather than the regional location dummy variable considered here. Longitudinal cracking, however, also may be due to loading if these cracks are found in the wheel path.[12] As the level of alligator cracking and other manifestations of distress such as rutting becomes pronounced, the effect of loading could be more significant and would require efforts to develop appropriate loading data for consideration in future modeling.

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