

The Prediction of LWST Values from DFT and CTM Measurements Using Linear and Nonlinear Regression Analyses

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ABSTRACT

The objective of this work is to develop statistical models to predict Locked Wheel Skid Trailer (LWST) skid numbers from Dynamic Friction Tester (DFT) and Circular Texture Meter (CTM) measurements conducted on asphalt pavement surfaces. The analyses conducted are descriptive as well as analytical. They include all descriptive measures along with linear and nonlinear regressions. For both analyses, DFT measurements at 20 km/h (12.5 mph) and 64 km/h (40 mph) and Mean Profile Depth (MPD) were used to predict LWST skid values. Furthermore, the International Friction Index (IFI) parameters (F_{60} and S_p) were used in an additional analysis to predict LWST skid values. Multiple linear regression techniques were used to identify the significant quantitative predictors. Model selection using stepwise regression showed that *DFT64* and *MPD* are statistically significant predictors. Moreover, regression analysis showed that *DFT20* is highly correlated with other predictors and therefore removed due to multicollinearity. Additionally, it was shown that F_{60} and S_p are also significant in predicting the dependent variable with slightly less correlation coefficients. Nonlinear regression technique was also utilized for the same purpose. In both cases, higher correlation coefficients were noticed when using the nonlinear method as opposed to the multiple linear regression method.

KEYWORDS: Friction, Texture, International Friction Index (IFI), Regression, Linear, Nonlinear.

INTRODUCTION

Pavement friction is important for the screening process of pavement surfaces to ensure their adequacy to control skid-related accidents all around the world. It is therefore adopted by State Departments of Transportation (DOTs) and the Federal Highway Administration (FHWA) along with the pavement industry in its public and private sectors. Pavement friction is an indicator of the safety level supplied by a pavement. It is defined as the ability of the pavement surface to prevent the loss of traction with the vehicle tire. Pavement friction or pavement skid resistance is

controlled by many factors, among which is bleeding, low aggregate abrasion resistance, particle angularity, surface roughness and texture, wet or dry conditions that determine the amount of lubrication on the surface, maximum nominal aggregate size used in the mixture design and the presence of debris and remains, among other factors.

Of these factors, pavement texture was found to be the most influencing. Pavement texture is the feature of the road surface that ultimately determines most tire-pavement interactions, including wet friction, noise, splash and spray, rolling resistance and tire wear (Henry, 2000). Pavement texture has been categorized into four ranges based on the wavelength of its components: microtexture, macrotexture, megatexture

and roughness or evenness. Wet pavement friction is primarily affected by the range described by microtexture and macrotexture, as can be seen in studies such as those conducted by Wilson and Dunn (2005) and Goodman et al. (2006). Therefore, a direct or indirect measure of pavement microtexture and macrotexture is required to better understand pavement surface characteristics.

OBJECTIVES

Many friction and texture measuring devices have been used to characterize asphalt and concrete pavement surfaces. Among all devices, the Locked Wheel Skid Trailer (LWST) has been adopted by State DOTs and the FHWA as well as by many others. The Dynamic Friction Tester (DFT) and the Circular Texture Meter (CTM), on the other hand, have proved to be two of the best devices for the purpose of hard surfaces characterization. The LWST, which is a full-scale friction measuring device, is considered to be relatively time-consuming and definitely requires full-scale traffic control for a long period and distance for the test to be successfully completed. The DFT, however, is designed to be compact and easy to carry and measurements can be made in a very short time with minimal traffic hindrance. The CTM, which is a companion device to the DFT, is also portable and easy to operate. It is for this reason that there is a need to enable the prediction of LWST friction values from easier-to-get DFT and CTM measurements through robust statistical analysis. This includes the multiple linear and nonlinear regression analyses to arrive at some reliable models for estimating LWST skid numbers. Due to the fact that DFT and CTM values can be used to compute the International Friction Index (IFI) parameters, analysis was extended to develop correlations with IFI terms and then a comparison study was conducted to reach at the best possible predicting model.

BACKGROUND

Over the years, numerous studies have developed correlations to predict friction values from other friction variables, or to predict friction values from pavement surface texture and/or roughness or to predict friction values from pavement surface characteristics including friction and texture. A summary of some of these studies is presented herein.

Yero et al. (2012) aimed at determining the correlation between the pendulum test value (PTV), texture depth (TD) and international roughness index (IRI) of various bituminous road surfaces. The results obtained from the study shows a weak or no correlation between the texture depth and the roughness index. But, the general trend shows that the higher the texture depth, the higher the roughness index and the pendulum test values. According to Bustos et al. (2006), the inclusion of texture measurements as a variable in estimating skid resistance values significantly enhanced the models' prediction power.

In an old study in California, poor correlation was found between the California Skid Tester (CST) and the Penn State Drag Tester when different types of surfaces were compared. A significant correlation existed when only Portland Cement Concrete (PCC) surfaces were used in the analysis. This is not surprising in view of the totally different configurations and test speeds of the two testers. Later, the correlation between the CST and a locked-wheel skid trailer was studied by measuring the friction results of seven types of pavement surfaces, including PCC and Asphalt Cement (AC). The locked-wheel skid trailer used two ribbed tires tested at a speed of 64 km/h (40 mph). The CST was first calibrated using locked wheels, smooth tires, wet pavement and a speed of 80 km/h (50 mph). For a better comparison, additional testing was performed using the locked-wheel skid trailer unit with its speed changed to 80 km/h (50 mph) and its ribbed tires replaced by smooth tires. For all the test conditions investigated, correlations indicated that the

CST results could be used to predict the BPR skid number. Then, the California Division of Highways conducted a correlation study between the CST and Arizona's Mu-Meter for a variety of surfaces. All tests were performed at 64 km/h (40 mph) on wet pavements. It was found that a linear correlation exists between the skid resistance values obtained by the two testers. Finally, Caltrans investigated methods to measure surface macrotexture and their correlations with skid resistance data acquired using the CST. Pavement surface macrotexture was measured by the Sand Patch test. A variety of pavement surfaces were tested. The results showed a general trend toward a higher skid number with increasing texture depth. The relationship, however, was neither clear nor definitive (Lu and Steven, 2006).

The Penn State University Drag Tester uses the same slider as the British Pendulum Tester (BPT), but it is normally operated at a lower speed than the BPT. Kummer reported good correlation between the two when using the same rubber for their sliders (Lu and Steven, 2006). Henry (2000) found that when the slip speed is 20 km/h (12 mph), the DFT friction correlates highly with the British Pendulum Number (BPN) values. BPT values are found to be significantly more variable than DFT values. The correlation between BPT and the Grip Tester was studied in Australia (Mackey, 2005). A limited number of data showed a correlation between measurements of the two testers when the Grip Tester was either towed at 50 km/h (30 mph) or pushed at 5 km/h (3 mph).

Correlation between the skid number and the stopping distance was also tried and a high one-to-one correlation was obtained (Lu and Steven, 2006). In 2002, Caltrans measured the skid resistance on several pavement sections using both the ASTM E274 skid trailer and the BPT. The data from this study did not produce a meaningful correlation between the two tests due to the considerable scatter and the limited range of data. However, the report suggested that it would be possible to develop a meaningful correlation between SN and BPN when more data were added and distinctions were made between the

different types of mixes (Caltrans, 2002). Gallaway et al. (1971) showed that the Mu-Meter and an ASTM E274 tester had a good correlation when both testers used tires without tread and both operated with the pavement wetted by sprinkler truck, but the correlation was not very good when the ASTM E274 tester strictly followed the specifications.

In 2008, Khasawneh and Liang conducted a correlation study that included simple and multiple linear regressions among the following variables: LWST skid numbers at 64 km/h (40 mph), DFT friction numbers at 64 km/h (40 mph), DFT friction numbers at 20 km/h (12.5 mph) and MPD measured using the CTM. DFT64 was used to account for macrotexture effect while DFT20 was incorporated into the regression analysis in order to account for microtexture effect due to the fact that microtexture is measured using low speed friction measuring devices (Wambold et al., 1995). Analysis results showed that LWST skid numbers at 64 km/h (40 mph) are highly correlated to DFT friction numbers at 64 km/h (40 mph). Predictive models for LWST skid numbers were developed. Nevertheless, data set used in this study was somewhat limited to only one year and the highly sophisticated nonlinear regression analysis was not employed which might increase the uncertainty involved in the developed models. Furthermore, the universal IFI concept was not considered.

According to the comprehensive literature review presented in this section, a robust correlation relating SN from the LWST and friction and macrotexture values from the DFT and CTM, respectively, is missing. Therefore, the main objective of this study is to enable the prediction of LWST skid resistance values from DFT and CTM measurements using highly sophisticated techniques. Additionally, the regression will also consider using the IFI terms in predicting LWST values for further clarification. Essentially, this effort should help in expediting the screening of pavement surfaces as part of the quality control and quality assurance as well as pavement control and monitoring programs.

METHODOLOGY

Data Compilation

Actual pavement sections were initially selected all with AC surfaces. The selection of these pavement sections is based on the criteria that each of the pavement section has adequate history of skid number measurements and documentation of traffic counts as well as the construction materials (Job Mix Formula - JMF). Each section was tested using the three devices included in the study; LWST, DFT and CTM. The average of two runs of each device on the same spot, left wheelpath, represents one data point. Tests were performed during the same time of the year in order to lessen the environmental and traffic effects on the collected data, since these factors are very important in determining friction and texture on the short-term and long-term basis. Measurements were taken for two consecutive years to end up having an adequate number of data points for a healthy statistical analysis and to ensure repeatability of measurements over years. Sites are located throughout the state of Ohio covering; districts 2, 3, 10, 11 and 12 (Khasawneh, 2008). Lack of skid resistance in the collected data could be attributed to the fact that measurements were taken in the summer months which might have caused bleeding of asphalt to the surface which, in turn, could have caused friction values to be lower than expected under ideal conditions.

Equipment

Among the many different types of full-scale friction measuring devices, the LWST has been known to collect repeatable and consistent data. It is for this reason that State DOTs and the FHWA have adopted the LWST as the standard friction measuring device. The LWST is a full slip device, since the measurements are carried out at a slip of 100 percent with the measuring wheel completely locked during testing. ASTM regulates the manufacturing and measuring standard of the LWST in ASTM E-274. The LWST measures the steady-state friction force on a

locked wheel on the wetted pavement surface as the wheel slides at a constant speed. The skid resistance of the paved surface is reported as skid number (SN), which is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100. Skid testing is conducted using a smooth tire (ASTM E-524) or a ribbed tire (ASTM E-501). Although pavement friction measurements can be conducted at different speeds, the standard test speed is 64 km/h (40 mph).

The DFT (ASTM E-1911) is an easy-to-use portable instrument to measure the dynamic coefficient of friction. The straightforward physical principles involved in the measurement of friction can solve a wide range of problems. The measured values are a continuous spectrum of dynamic coefficient of friction. Measurement can be made in a very short time with minimal interference with traffic, the device is designed to be compact and easy to carry, the device reports the friction graphically as a function of speed from 0 to 80 km/h (0 to 50 mph) at a contact pressure similar to that of typical motor vehicles, it is powered by 12V DC (automobile battery) and 100V AC and an optional AC/DC converter is available, the standard rubber of the slider assembly is synthetic rubber as specified in the ASTM E-501 specification, and the slider assembly can readily be replaced at measuring sites. Essentially, the tire rubber is pressed against the road surface with a force W (load that is enough to produce pressure equivalent to tire pressure), and a horizontal force F is applied to move the rubber with a specific speed. This force F is due to the friction. When F and W are known, the coefficient of friction, μ , is determined from this relationship (<http://www.tics.hu/DFTester.htm>):

$$\mu = \frac{F}{W} \quad (1)$$

The reference method for determining pavement macrotexture has historically been the volumetric sand patch method (ASTM E-965), which is a simple test, but its results are operator dependent (Henry, 2000). The Circular Texture Meter (CTM) is a road surface

macrotexture profiler that uses a laser-displacement sensor to measure the vertical profile of a pavement surface. The CTM software calculates and reports the Mean Profile Depth (MPD) and Root Mean Square (RMS) statistics that characterize profile macrotexture. The CTM is designed to measure the same circular track that the DFT measures. The device measures the profile of a circle 284 mm (11.18 in) in diameter, and the circumference, 892 mm (35.12 in), of that circle is divided into eight segments of 111.5 mm (4.39 in) in length. The average MPD and/or RMS are determined for each segment, and these values are used to calculate the overall average. Two of the eight segments (A and E) measure profile in the direction of travel, while two others (C and G) measure it perpendicular to the direction of travel (ASTM E-2157).

International Friction Index (IFI)

The International Friction Index (IFI) was developed as a common scale for the reporting of pavement friction measurements by the Permanent International Association of Road Congresses, PIARC (Wambold et al., 1995). IFI is currently being adopted worldwide as the standard skid resistance measure. Moreover, American Society for Testing and Materials (ASTM) adopted the IFI and formulated the ASTM E1960 to help calculate the IFI for a specific pavement surface. The IFI consists of two terms: (1) the speed constant, S_p , which is a function of pavement macrotexture, and (2) the wet friction of a pavement, F_{60} , at 60 km/h, that depends on a measured friction value, the slip speed and the speed constant. The detailed procedure used to determine the IFI terms is explained elsewhere (Wambold et al., 1995; Khasawneh, 2008). Once IFI parameters are determined, the calibrated friction at any other slip speed can be calculated. Another advantage of the IFI is that the value of F_{60} for a pavement will be the same regardless of the slip speed. That permits the test vehicle to operate at any safe speed. Finally, the standard ASTM E1960 describes a procedure to calibrate devices that did not participate in the experiment.

Study Approach

The statistical analysis was carried out and results reported for two cases using two analysis methods. Linear and nonlinear regression techniques were utilized before and after the removal of existing outliers. Firstly, all collected data points before removing any outliers were statistically analyzed using the stepwise multiple linear regression technique. Models were developed once using DFT_{20} , DFT_{64} and MPD as predictors and another time using the IFI parameters; namely, F_{60} and S_p as predictor variables. After that, outliers were removed and same analysis repeated to end up getting different correlation constants with different models and coefficients of determination (R^2). Secondly, data points before the removal of outliers were statistically analyzed using the nonlinear regression technique. Models were developed once using DFT_{20} , DFT_{64} and MPD as predictors and next using the IFI parameters (F_{60} and S_p) as predictors. Then, outliers were removed and similar analysis performed that resulted in different models and models' strengths.

The R^2 value implies the percent of variability in dependent variable explained by the model (independent variables or predictors). Regression analysis is used to identify the significance of quantitative predictors on the dependent variable and to estimate their relative importance. However, model diagnostics must be considered. Luckily, the normality assumption which is necessary in the parametric regression analysis to hypothesize testing and model selection is not violated in all of our models. Furthermore, multicollinearity among the predictors as well as the presence of outliers must be checked. Regarding multicollinearity, a popular procedure available in the statistical packages is to drop the predictors from the fitted model which are highly correlated with other predictors. Concerning outliers, an analysis will be performed using the full data set (with outliers) and another analysis using the data set after the removal of outliers. Results of both analyses were reported and differences discussed.

RESULTS AND DISCUSSION

Results were generated by thoroughly analyzing quantitative predictors. First visual examination of the data via box-plot was considered to verify the existence of any outliers or anything unusual in the data. Relevant descriptive statistics, such as counts, minimum, maximum, means, medians and standard deviations were calculated. Ordinary multiple linear regression analysis was used to identify significant quantitative predictors on the LWST dependent variable. The regression analysis also included checking the model assumptions in the regression model (homoscedasticity, independence and normality), in addition to the examination of two important features of the data; multicollinearity and outliers or influential points. Analysis of variance (ANOVA) tables along with models' statistical characteristics were obtained and reported. Finally, plots showing the goodness of developed models were also prepared to graphically present the models' strength in predicting the dependent variable (LWST). Similarly, nonlinear regression was performed to detect any potential improvement using this sophisticated technique in predicting LWST values. Any data point with Studentized residual, which is an important technique in the detection of outliers, of more than 2 was detected and then removed. The selection of Studentized residual of 2 as a cutting point in identifying outliers is most common in statistics; however, selecting other values may slightly alter models' constants and prediction power. The Statistical Package for Social Sciences (SPSS Inc., Version 17) was used to perform the statistical analysis. The fitted regression equations using the above analysis procedure are as follows:

Linear Regression Model 1 (DFT20, DFT64 and MPD) before Outliers' Removal

Table 1 shows the descriptive statistics (counts, minimum, maximum, mean and standard deviation) for the collected data of all models. Table 2, on the other

hand, presents the ANOVA table that contains the adjusted R^2 , standard error of the estimate (SEE), the F-value and the significance or the P-value. The most important of all is the P-value that indicates whether the developed model is statistically significant or not; as a value less than 0.05 indicates a statistically significant model and a value higher than 0.05 indicates the opposite. Adjusted R^2 is used in place of R^2 , if and only if, more than one predictor is used in the model in order to avoid misleading increase in its value. It can be seen that model 1, presented in Equation 2, is statistically significant on the 0.05 significance level. Table 3 shows the correlation constants, standard error, t-value and the significance or the P-value. It is clearly shown that the constant, **DFT64** and **MPD** are all significant in formulating model 1. Figure 1 plots predicted LWST values *versus* measured LWST values. Best fit line along with R^2 and the equality line are also labeled on the plot. Similar plots were prepared, though not shown, for all developed models.

$$LWST = 12.728 + 0.726DFT64 + 2.380MPD \quad (2)$$

Linear Regression Model 2 (F60 and S_p) before Outliers' Removal

Similar analysis was carried out for a new data set using **F60** and S_p as predictors. Equation 3 represents the second model and is shown below. Tables 1, 2 and 3 show descriptive statistics, ANOVA table and correlation constants along with their significance. It is clear that the model is significant on the 0.05 significance level. It is also clear that the constant, **F60** and S_p are significant in formulating model 2.

$$LWST = 11.174 + 0.888F60 + 0.043S_p \quad (3)$$

Linear Regression Model 3 (DFT20, DFT64 and MPD) after Outliers' Removal

The first two models were modified for a new data set after outliers have been removed. Equation 4 shows the third model that predicts LWST skid values from

the three predictors *DFT20*, *DFT64* and *MPD*. Tables 1, 2 and 3 show descriptive statistics, ANOVA table and correlation constants along with their significance. It is clearly shown that the model is significant as well as the constant, *DFT64* and *MPD* predictors.

$$LWST = 12.390 + 0.713DFT64 + 3.284MPD \quad (4)$$

Linear Regression Model 4 (F60 and Sp) after Outliers' Removal

Equation 5 shows the fourth model that predicts LWST numbers from the *F60* and *S_p* after outliers' removal. Tables 1, 2 and 3 show descriptive statistics, ANOVA table and correlation constants along with their significance. It is again proven that the model is significant, regression constant, *F60* and *S_p* predictors are also significant.

$$LWST = 10.727 + 0.874F60 + 0.053S_p \quad (5)$$

Table 1. Descriptive statistics for the collected data of the four models

Variable	Symbol	Minimum	Maximum	Mean	Standard Deviation	Remarks
Model 1						
Dynamic Friction Tester value at 64 mph	DFT64	31.2	68.5	48.952	8.0671	Predictor
Dynamic Friction Tester value at 20 mph	DFT20	26.6	77.7	53.909	12.7322	Predictor
Mean Profile Depth (mm)	MPD	0.30	1.97	0.6740	0.30274	Predictor
Locked Wheel Skid Trailer Value at 64 mph using ribbed tire	LWST	29.11	65.62	49.8639	7.57823	Response
Model 2						
Friction Parameter of the IFI	F60	25.19	55.81	39.9346	6.44575	Predictor
Texture Parameter of the IFI	Sp	41.11	190.91	74.6547	27.15548	Predictor
Locked Wheel Skid Trailer Value at 64 mph using ribbed tire	LWST	29.11	65.62	49.8639	7.57823	Response
Model 3						
Dynamic Friction Tester value at 64 mph	DFT64	31.2	68.5	49.330	8.1186	Predictor
Dynamic Friction Tester value at 20 mph	DFT20	26.6	77.7	54.756	12.6325	Predictor
Mean Profile Depth (mm)	MPD	0.30	1.97	0.6789	0.31237	Predictor
Locked Wheel Skid Trailer Value at 64 mph using ribbed tire	LWST	32.75	65.23	49.8161	7.06061	Response

Model 4						
Friction Parameter of the IFI	F60	25.19	55.81	40.2389	6.45514	Predictor
Texture Parameter of the IFI	Sp	41.11	190.91	75.0783	27.93167	Predictor
Locked Wheel Skid Trailer Value at 64 mph using ribbed tire	LWST	32.75	65.23	49.8730	7.07499	Response

Table 2. Analysis of variance test results for the four models

Source	Sum of Squares	df	Mean Square	F	Sig.
Model 1					
Regression	6472.478	2	3236.239	159.811	0.001
Residual	3462.829	171	20.250		
Total	9935.308	173			
<i>Adjusted R² = 64.7%</i>			<i>Standard Error of the Estimate (SEE) = 4.500</i>		
Model 2					
Regression	6453.991	2	3226.995	158.508	0.001
Residual	3481.317	171	20.359		
Total	9935.308	173			
<i>Adjusted R² = 64.6%</i>			<i>Standard Error of the Estimate (SEE) = 4.512</i>		
Model 3					
Regression	6080.769	2	3040.385	264.105	0.001
Residual	1795.876	156	11.512		
Total	7876.645	158			
<i>Adjusted R² = 76.9%</i>			<i>Standard Error of the Estimate (SEE) = 3.392</i>		
Model 4					
Regression	6078.806	2	3039.403	253.820	0.001
Residual	1880.021	157	11.975		
Total	7958.827	159			
<i>Adjusted R² = 76.1%</i>			<i>Standard Error of the Estimate (SEE) = 3.460</i>		

Table 3. Statistical characteristics for the four models

Predictor	Coefficient	Std. Error	t	Sig.
Model 1				
(Constant)	12.728	2.108	6.039	0.001
DFT64	0.726	0.045	16.277	0.001
MPD	2.380	1.188	2.003	0.047
Model 2				
(Constant)	11.174	2.200	5.079	0.001

F60	0.888	0.055	16.206	0.001
Sp	0.043	0.013	3.346	0.001
Model 3				
(Constant)	12.390	1.663	7.451	0.001
DFT64	0.713	0.035	20.283	0.001
MPD	3.284	0.914	3.592	0.001
Model 4				
(Constant)	10.727	1.761	6.091	0.001
F60	0.874	0.044	19.894	0.001
Sp	0.053	0.010	5.215	0.001

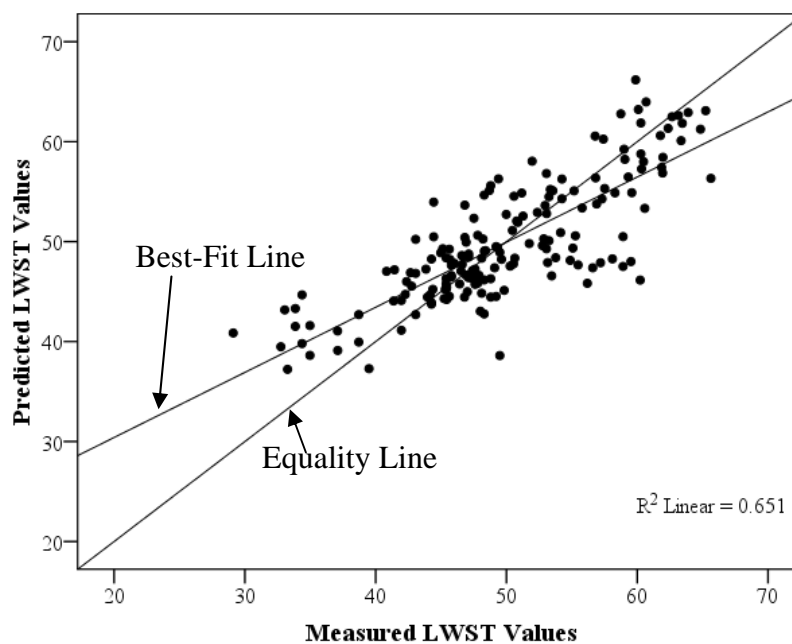


Figure (1): Proposed model 1 predicted *versus* measured values

Nonlinear Regression Model 5 (DFT20, DFT64 and MPD) before Outliers' Removal

The nonlinear regression analysis was carried out to detect any possible enhancement in the above four models (where multiple linear regression technique was used) in terms of R^2 and all other model characteristics. To run the nonlinear analysis, curve fitting software is needed to select the best fit for each predictor from a pool of existing functions. CurveExpert version 1.40, which is a curve fitting

system for Windows, was used for this purpose. Later, the best fit functions are multiplied by each other and appropriate constants are determined using the SPSS nonlinear capabilities. It can be seen from model number 5 (shown in Equation 6), as compared to model 1, that R^2 went up by 5% to reach 69.7%. In this model, as well as model 1, *DFT20*, *DFT64* and *MPD* were used as predictors. Figure 2 plots the predicted LWST values *versus* the measured LWST values. Best fit line along with R^2 and the equality line are all shown and

labeled on the plot.

$$LWST = \left[-30.125 + 4.375 \times DFT20 + -0.085 \times DFT20^2 + 0.001 \times DFT20^3 \right] \times \left[13.239 \times \exp^{\frac{-39.946}{DFT64}} \right] \times \left[\frac{0.210 \times -11412.890 + 0.223 \times MPD^{35.980}}{-11412.890 + MPD^{35.980}} \right] \tag{6}$$

Nonlinear Regression Model 6 (F60 and Sp) before Outliers' Removal

66.5%, increasing by 1.9% as compared to model 2. In these two models, *F60* and *Sp* were used as predictors.

For model number 6, Equation 7, R² went up to

$$LWST = \left[26124.541 \exp^{(-28.393/F60)} \right] \times \left[\frac{1}{-0.209 \times S_p + 270.219} \right] \tag{7}$$

Nonlinear Regression Model 7 (DFT20, DFT64 and MPD) after Outliers' Removal

In these two models, *DFT20*, *DFT64* and *MPD* were used as predictors. Model 7 is as shown in Equation 8 below.

For model number 7, it can be seen that R² went up to 79.2%, increasing by 2.3% as compared to model 3.

$$LWST = \left[-3.312 + 0.701 \times DFT20 + -0.014 \times DFT20^2 + 8.507E-5 \times DFT20^3 \right] \times \left[0.058 \times \exp^{\frac{-35.823}{DFT64}} \right] \times \left[\frac{216.908 \times -1507469.441 + 224.774 \times MPD^{40.550}}{-1507469.441 + MPD^{40.550}} \right] \tag{8}$$

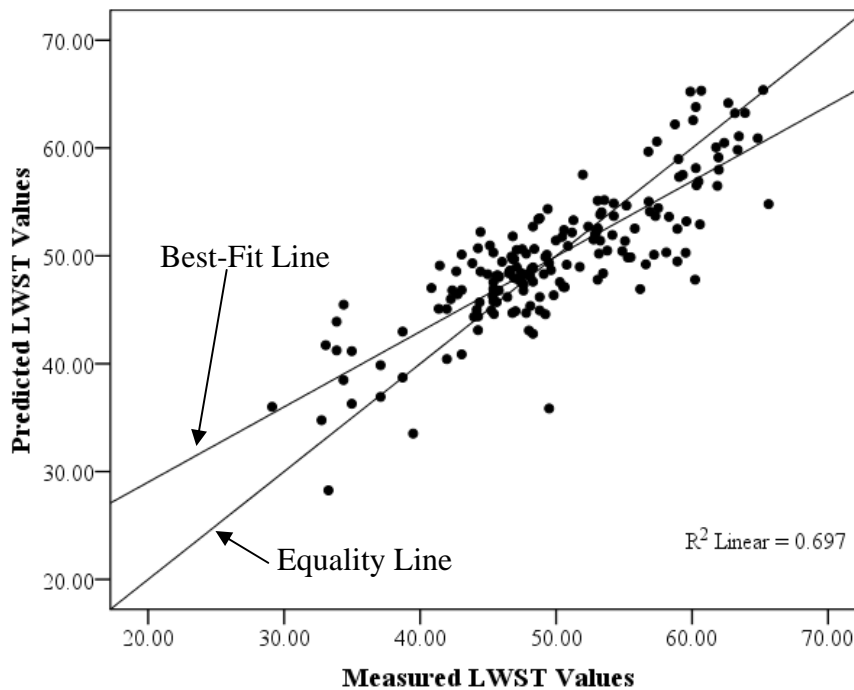


Figure (2): Proposed model 5 predicted versus measured values

Nonlinear Regression Model 8 (F60 and Sp) after Outliers' Removal

For model number 8, it can be seen that R² went up

$$LWST = [3483.545 \exp^{(-28.367/F60)}] \times \left[\frac{1}{-0.032 \times S_p + 36.609} \right] \quad (9)$$

SUMMARY AND CONCLUSIONS

Statistical models for the estimation of LWST friction values from DFT and CTM measurements were developed. The analysis conducted includes all descriptive measures as well as linear and nonlinear regression techniques. Basically, the developed models in this study should help in expediting the screening of pavement surfaces as part of the quality control and quality assurance as well as pavement control and monitoring programs. The main conclusions attained from this study are summarized below:

1. Linear and nonlinear regression methods resulted in significant models for the prediction of LWST values from friction and texture measurements at the 0.05 significance level.
2. In general, friction and texture measurements using DFT and CTM, respectively, proved to be good predictors in estimating the LWST values. Hence, there is a chance to replace the difficult-to-run LWST by the easily operated DFT and CTM

to 77.9%, increasing by 1.8% as compared to model 4. In these two models, *F60* and *S_p* were used as predictors. Model 8 is as shown in Equation 9 below.

devices.

3. There was an increase in the coefficient of determination values when using nonlinear regression compared to linear regression.
4. There was a significant increase in models' prediction strength after the detection and removal of outliers and influential points (so called unusual points).
5. As a general rule, using DFT and CTM values produced better models for predicting LWST values as opposed to using IFI parameters for the same purpose.
6. The best model among all is the nonlinear model after the removal of unusual points when using *DFT20*, *DFT64* and *MPD* as predictors with R² equals 79.2%. Therefore, it can be concluded that this model is sufficient in predicting asphalt pavement surface friction characteristics to be used in pavement safety procedures and incorporated into pavement management systems.

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