# Accelerated Superpave Mix Testing Models Using Hamburg Wheel-Tracking Device

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ABSTRACT: Lives of Superpave pavements with mixes that are out-of-specifications for in-place density and design air voids can be estimated based on the Hamburg Wheel-Tracking Device (HWTD) test results. HWTD has gained popularity for testing rutting and stripping potential of asphalt mixes. However, a typical HWTD test takes about six to six and one-half hours to complete. This study focused on reducing test duration by developing accelerated mix testing models based on statistical analysis of shorter-duration test results. Five fine-graded Superpave mixtures with 12.5-mm Nominal Maximum Aggregate Size (NMAS) were selected for this study with design air voids of 4%, simulated in-place density of 93%, two test temperature, and three load levels. Six-inch field cores from three projects were also tested in HWTD at two temperature and three load levels for model development for field mixes. The average number of wheel passes to 20-mm rut depth in the HWTD tests was used in the statistical analysis to build accelerated mix testing models. The results show that good consistency between the predicted and the observed test results is obtained when higher temperature and standard load levels are used. The test duration of HWTD can thus be reduced to two hours or less. This is expected to increase the use of HWTD as an effective tool for the quality control and quality assurance (QC/QA) of Superpave mixtures.

KEY WORDS: Superpave pavements, Hamburg wheel-tracking device, hot-mix asphalt, accelerated mix testing models, moisture damage.

## 1 INTRODUCTION

The Kansas Department of Transportation (KDOT) is increasingly using Superpave mixtures that may be susceptible to moisture damage. The moisture susceptibility is currently evaluated by the Kansas standard test method, KT-56 which closely follows American Association of State Highway and Transportation Officials (AASHTO) test method AASHTO T 283, Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage. Currently specified sampling and testing frequency chart of KDOT for bituminous construction items for the Quality Control/Quality Assurance (QC/QA) projects requires that one KT-56 test be performed by the contractor on the first lot, and then one test per week or 10,000 tons (Mg).

KDOT specifications also require that the bituminous mixture shall have a minimum Tensile Strength Ratio (TSR) of 80%. Since this test is time consuming, it often happens that the contractor already has paved a substantial area of the pavement that might have the mixture that does not satisfy this criterion. As of now, there is no “rapid” test method available to find out mixtures that are susceptible to moisture damage. Hamburg Wheel-Tracking Device (HWTD) has the potential to characterize moisture sensitivity of asphalt mixes and to predict field performance (Hicks 1991, Lai 1989, Aschenbrener 1995, Buchanan 1997). The HWTD test was found to be sensitive to aggregate quality, asphalt cement stiffness, short-term aging duration, asphalt source or refining process, antistripping treatments, and compaction temperature (Pan and White 1999, Izzo and Tahmoressi 1999). The test is also gaining popularity for testing rutting and stripping potential of hot-mix asphalt (HMA) mixes. However, a single HWTD test takes about six to six and one-half hours. If the test duration can be reduced significantly, HWTD will be an effective tool for QC/QA of HMA.

## 2 OBJECTIVES

The objective of this project was to develop accelerated mix testing models using Hamburg Wheel-Tracking Device (HWTD) test results. It was assumed that two predominant distresses that would occur due to non-conforming mixtures are stripping and rutting.

## 3 ACCELERATED LIFE MODELING

Overstress testing consists of running a product at higher than normal levels of some accelerating stress(es) to shorten product life or to degrade product performance faster. Typical accelerating stresses on asphalt pavement are higher service temperature or traffic loads. Accelerated degradation testing involves overstress testing. Instead of life, product performance is observed as it degrades over time. A model for performance degradation is fitted to such performance data and used to extrapolate performance and time of the failure. Thus the failure and the life can be predicted before any specimens fails (Nelson 1990).

### 3.1 Survival Analysis

Survival analysis generally refers to statistical methods for analyzing survival or time-to-event data. The data can be generated from diverse fields, such as medicine, biology, public health, epidemiology, engineering, economics and demography (Klein and Moeschberger 1997). For example, let X be the time until some specified event. This event may be death, the development of some disease, equipment breakdown, etc. X is usually taken as a non-negative random variable from a homogeneous population. Four functions characterize the distribution of X: (1) *Survival function*, which is the probability of survival, beyond time x; (2) *Hazard rate (function)* which is the chance an individual of age x experiences the event in the next instant; (3) *Probability density function*, which is the unconditional probability of the event occurring at time x; and (4) *Mean residual probability life* at time x, which is the mean time to the event of interest, given that the event has not occurred at x. If any of these parameters is known, then the other three can be uniquely determined (Klein and Moeschberger 1997).

## 3.2 Weibull Distribution

The Weibull family distribution is a very flexible model for survival analysis. Its *survival function*, shown in Figure 1, for Weibull distribution is given by $S^{X}(x) = \exp(-\lambda x^{\alpha})$. The *hazard rate* is expressed as $h^{X}(x) = \lambda\alpha x^{\alpha-1}$. When the log transform of time is taken, the univariate survival function for Y = ln X can be expressed as in Equation 1.

$$Sy(y) = e^{(-\lambda e \alpha y)} \tag{1}$$

If we redefine the parameters as $\lambda = \exp(-\mu/\sigma)$ and $\sigma = 1/\alpha$, then, *Y* follows the form of a log linear model as given in Equation 2.

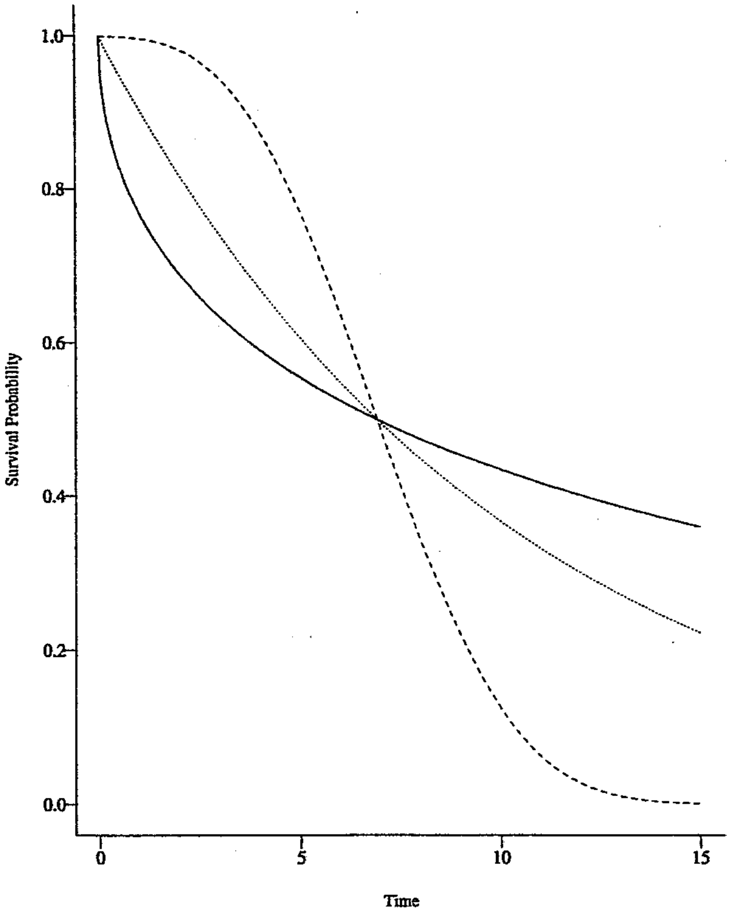


Figure 1: Weibull survival functions for $\alpha = 0.5$, $\lambda = 0.26328$ ( ——— ); $\alpha = 1.0$, $\lambda = 0.1$ (………); $\alpha = 3.0$, $\lambda = 0.00208$ (---------) (Klein and Moeschberger 1997).

$$\mathrm{Y} = \ln \mathrm{X} = \mu + \sigma W \tag{2}$$

where W is the extreme value distribution with *probability density function,*

$$fw(w) = e^{\left(w - e^{w}\right)} \tag{3}$$

*and survival function,*

$$Sw(w) = e^{\left(-e^{w}\right)}. \tag{4}$$

As will be shown later, one of the survival functions (exponential) shown in Figure 1 can be used to analyze the HWTD test results.

## 4. EXPERIMENTAL DESIGN

Five fine-graded Superpave mixtures with 12.5-mm Nominal Maximum Aggregate Size (NMAS) were selected for this study. Four mixtures were sampled from four different projects, each located in one KDOT administrative district and done by one contractor. One mixture was selected from the pavements of the accelerated pavement testing (APT) program at the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University. Replicate test specimens were prepared at design asphalt content (air void of 4% @ $N_{design}$ gyrations). The Superpave Gyratory compactor-compacted samples had 7 $\pm 1$% air voids at the completion of compaction. Samples were tested in HWTD at two temperature levels (50°C and 60°C) and five load levels (705, 750, 795, 840, and 885 N). Thus, the experiment involved a total of 50 sets (5 projects x 2 temperature levels x 5 load levels) of samples. However, load levels of 840 and 885 N were added in the experimental design after preliminary test results were obtained. Thus not all mixtures were tested under these load levels.

Table 1 shows the characteristics of the mixtures under this study. The binder grade for four mixtures was PG 64-22 and one mixture had PG 64-28. The asphalt contents of the base design mixtures (4% air voids @ $N_{design}$) varied from 4.9% to 5.4%. The mixture properties, reported in Table 1, were obtained from the design data. All properties satisfied Superpave and current KDOT criteria.

Table 1: Properties of the Superpave mixes

| Route | Design ESALs (millions) | $N_{design}$ | PG Binder Grade | Asphalt Content (%) | Air Voids (%) at $N_{des}$ | VMA (%) | VFA (%) | Dust-Binder Ratio | %$G_{mm}$ at $N_{ini}$ | % $G_{mm}$ at $N_{max}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| K-4 | 0.4 | 75 | PG 64-22 | 4.9 | 4.36 | 13.9 | 68 | 0.7 | 88.8 | 96.6 |
| US-24 | 0.7 | 75 | PG 64-22 | 5.0 | 3.62 | 14.1 | 74 | 0.9 | 90.4 | 97.1 |
| US-50 | 4.5 | 100 | PG 64-22 | 5.4 | 4.10 | 14.6 | 70 | 0.6 | 88.4 | 96.9 |
| US-83 | 2.2 | 75 | PG 64-22 | 4.9 | 4.38 | 13.9 | 68 | 1.1 | 89.7 | 96.4 |
| CISL | 2.9 | 75 | PG 64-28 | 4.9 | 4.36 | 14.0 | 69 | 0.7 | 88.8 | 96.6 |

Figure 2 shows the aggregate gradations of the mixes used in this study. It is observed that only one mixture (US-24, District III) had a much finer gradation compared to others.

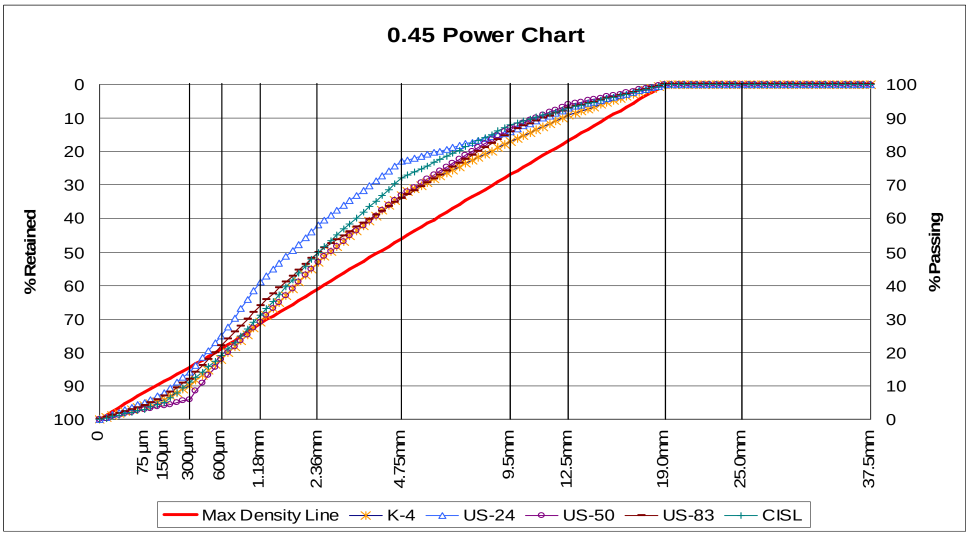


Figure 2: Aggregate gradation charts for the mixtures.

# 5 HAMBURG WHEEL-TRACKING DEVICE (HWTD) TESTING

## 5.1 Test Specimens Preparation

For each mix, replicate specimens of HWTD test were compacted at 7 ± 1% air voids. The theoretical maximum specific gravity ($G_{mm}$) of the loose mixtures and bulk specific gravity ($G_{mb}$) of the compacted samples were also determined. KDOT standard test methods KT-39 (AASHTO T209) and KT-15 (AASHTO T166) Procedure III were used to determine $G_{mm}$ and $G_{mb}$, respectively. The air voids in the compacted specimen were calculated using Equation (5):

$$\% AirVoids = \frac{100 \times (G_{mm} - G_{mb})}{G_{mm}} \tag{5}$$

## 5.2 Test Equipment

HWTD used in this study is capable of testing a pair of samples simultaneously. Figure 3 shows the Hamburg wheel tester at Kansas State University. These samples were extensively used by Izzo and Tahmoressi for studying Texas mixtures and in the development of Texas test method Tex-242 (Izzo and Tahmoressi 1999). In this study, this test method was followed. The samples were submerged under water at 50°C or 60°C.

The wheel of HWTD is made of steel and is 47 mm wide. The wheel applied a load of 705 N and made 52 passes per minute. Each sample was loaded for 20,000 passes or until 20-mm vertical deformation (rut depth) occurred at any point on the sample. The maximum velocity of the wheel reached was 340 mm/sec, which occurred at the center of the sample. Around six to six and one-half hours were required for a test for a maximum of 20,000 passes. Rut depth or deformation was measured at 11 different points along the length of each sample with a Linear Variable Differential Transformer (LVDT).

An acceptable mix was considered to have less than 20-mm rut depth after 20,000 passes at 50°C following Colorado DOT practice (Aschenbrener 1995). In this study, the number of wheel passes to 20-mm rut depth was used in accelerated test modeling.

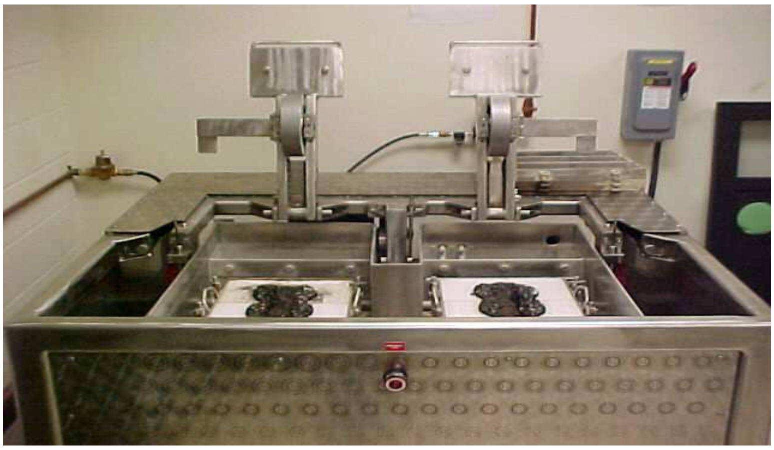


Figure 3: Hamburg Wheel-Tracking Device at Kansas State University.

## 5.3 HWTD Test Results

Table 2 shows the Hamburg wheel tester results in terms of the average number of passes and average wheel passes.

Table 2: Summary of HWTD test results (Average number of wheel passes)

| Route | Temp ($^0C$) | Wheel Passes at 705 N | Wheel Passes at 750 N | Wheel Passes at 795 N | Wheel Passes at 840 N | Wheel Passes at 885 N |
|---|---|---|---|---|---|---|
| K-4 | 50 | 13,700 | 18,730 | 15,950 | N/A | N/A |
| | 60 | 7,230 | 4,075 | 3,995 | N/A | N/A |
| US-24 | 50 | 17,625 | 17,390 | 16,650 | 11,210 | 13,385 |
| | 60 | 3,535 | 2,565 | 3,180 | 3,335 | 1,400 |
| US-50 | 50 | 20,000 | 20,000 | 20,000 | 8,420 | 7,450 |
| | 60 | 5,355 | 9,150 | 4,295 | 2,640 | 2,170 |
| US-83 | 50 | 20,000 | 20,000 | 20,000 | 11,260 | 15,770 |
| | 60 | 7,145 | 3,970 | 7,025 | 3,500 | 2,845 |
| CISL | 50 | 20,000 | 18,070 | 15,055 | N/A | N/A |
| | 60 | 5,390 | 4,020 | 4,625 | N/A | N/A |

Notes: Failure Criteria: 20 mm maximum rut depth or 20,000 passes whichever comes first;
A liquid anti-stripping agent (0.5%) was used only in District VI; N/A – not available.

# 6 STATISTICAL ANALYSIS

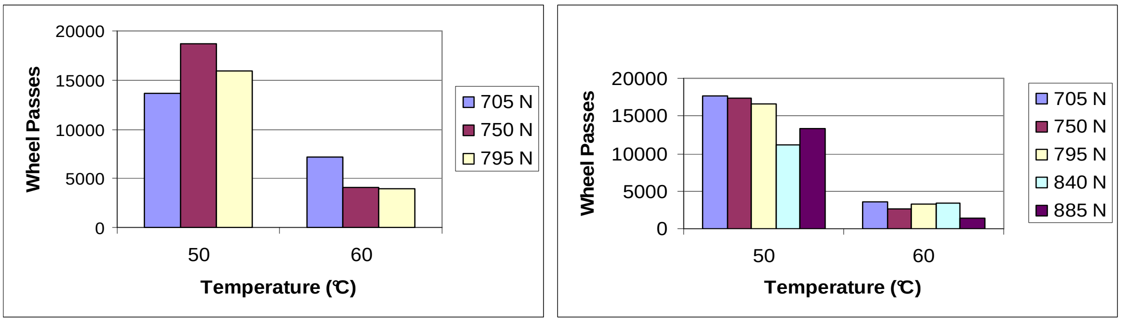
## 6.1 Influence of Temperature, Load, and Air Voids

The effect of temperature, load levels, and air voids levels on the HWTD test results was studied using LIFEREG procedure in SAS software (SAS User’s Guide 1982, SAS Online Document 2008). LIFEREG procedure was performed to develop accelerated testing model using HWTD test data by fitting with a Weibull distribution and to test the effect of different factors on the dependent (response) variable. PROC LIFEREG procedure fits parametric accelerated failure time models to the survival data that may be left, right, or interval censored (SAS Online Document 2008). The LIFEREG procedure estimates the parameters by maximum likelihood method using a Newton-Raphson algorithm (SAS Online Document 2008).

As mentioned earlier, the response variable to be studied was the number of wheel passes to reach a maximum 20-mm rut depth. The model used in the LIFEREG procedure is shown in Equation (6):

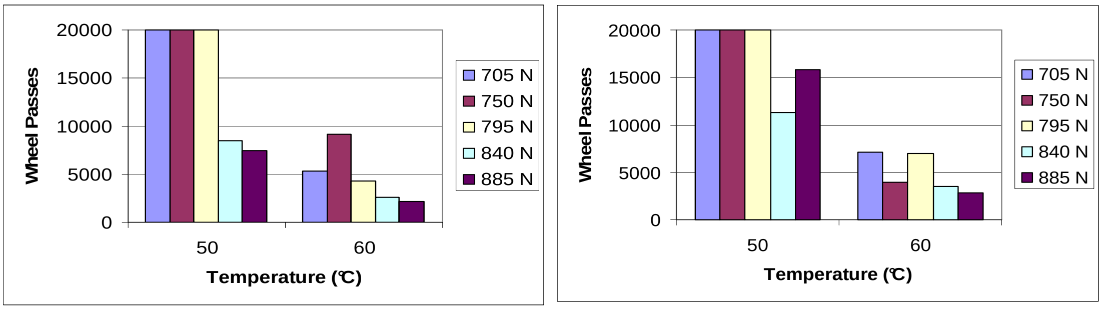
$$Ln(wheelpasses) = \beta_0 + \beta_1 Temperature + \beta_2 Load + \beta_3 AirVoids + \sigma\varepsilon \qquad (6)$$

where Temperature = Temperature effect; Load = Load effect;
Air Voids = Air voids effect; σ = Shape factor (1 for exponential case);
ε = Error term; and $\beta_0, \beta_1, \beta_2, \beta_3$ = Coefficients.



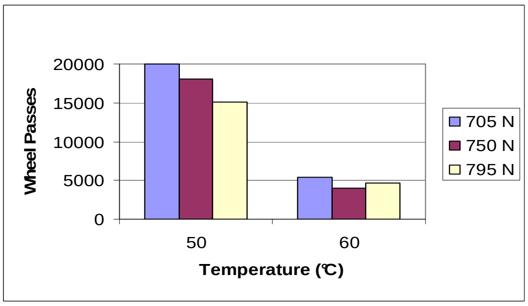
(a) K-4 Project

(b) US-24 Project



(c) US-50 Project

(d) US-83 Project



(e) CISL Project

Figure 4: HWTD test results.

Figure 4 illustrates the comparison of the number of wheel passes to reach 20-mm rut depth at different temperatures and load levels. The steeper slope of the plot at 60°C indicates that temperature change has more pronounced effect on the number of wheel passes to 20-mm rut depth than the load change.

The air void was added as a mixture characteristic because it varied from 6% to 8% and its effect on the HWTD test results is well known for in-place pavements (Gogula et al. 2003). HWTD test results are called right censored if the wheel passes reached 20,000 before 20-mm rut depth is obtained. Two projects had 30% censored data and one project had 17% of censored data and other two projects did not have any censored data. The Weibull residual analysis plots with SAS indicated that there is no significant difference between the models with interaction of temperature and load levels and model without the interaction term. Thus, no interaction term was included in the model.

Table 3 presents the summary of accelerated mix testing models developed for all projects. The results show that for almost all mixtures temperature, load level and air void are all significant.

Table 3: Summary of accelerated mix testing models

| Route | District | Parameter | Models | | |
|---|---|---|---|---|---|
| | | | Estimate | p-value | Significant |
| K-4 | I | Intercept | 19.1588 | < 0.0001 | * |
| | | Temp. ($^0$C) | - 0.1200 | < 0.0001 | * |
| | | Load (N) | - 0.0040 | 0.0562 | * |
| | | Air Voids (%) | - 0.0504 | 0.8084 | |
| US-24 | III | Intercept | 19.9521 | < 0.0001 | * |
| | | Temp. ($^0$C) | - 0.1618 | < 0.0001 | * |
| | | Load (N) | - 0.0021 | 0.0180 | * |
| | | Air Voids (%) | - 0.0836 | 0.4941 | |
| US-50 | V | Intercept | 28.8328 | < 0.0001 | * |
| | | Temp. ($^0$C) | - 0.1560 | < 0.0001 | * |
| | | Load (N) | - 0.0120 | < 0.0001 | * |
| | | Air Voids (%) | - 0.1995 | 0.4941 | |
| US-83 | VI | Intercept | 24.2580 | < 0.0001 | * |
| | | Temp. ($^0$C) | - 0.1643 | < 0.0001 | * |
| | | Load (N) | - 0.0060 | 0.0023 | * |
| | | Air Voids (%) | - 0.1675 | 0.4409 | |
| CISL | I | Intercept | 33.8756 | 0.0005 | * |
| | | Temp. ($^0$C) | - 0.1406 | < 0.0001 | * |
| | | Load (N) | - 0.0122 | 0.0246 | * |
| | | Air Voids (%) | - 1.0209 | 0.1076 | ** |
| All Projects | | Intercept | 21.1644 | < 0.0001 | * |
| | | Temp. ($^0$C) | - 0.1472 | < 0.0001 | * |
| | | Load (N) | - 0.0050 | < 0.0001 | * |
| | | Air Voids (%) | 0.0058 | 0.9324 | |

Notes: * Significant at 5% level of significance; ** Significant at 10% level of significance.

The analysis was done individually for each project since the mixture materials (except the binder for four out of five projects) varied from project to project. An example exponential accelerated life model (a special case of Weibull distribution), given in Equation (7), has been fitted to the HWTD test data from the K-4 project. Since these models are nonlinear, traditional means of examining "goodness" of linear model like the coefficient of determination ($R^2$) is not applicable. Thus a residual plot analysis was done. The "goodness of fit" was confirmed by the predicted and observed values falling around the $45^o$ line.

$$WP = e^{(19.1588 - 0.12T - 0.004L - 0.0504A)} \tag{7}$$

where *WP* = wheel passes; T = temperature in °C; L = load in N; and A = air voids in %.

For all mixtures, about 7,000 repetitions were needed for failure at $60^oC$ temperature and 705 N load levels. This would translate into slightly over two hours of testing time (about 2 hours 15 minutes) in the HWTD test.

## 7. FIELD SAMPLE TESTING

For verification of this methodology for field samples, 150-mm diameter cores were collected from three pavements in three different KDOT administrative districts (District I, III, and VI). These projects also had fine graded, 12.5-mm Nominal Maximum Aggregate Size (NMAS) Superpave mixtures (SM-12.5A) with PG 64-22 binder. HWTD tests were conducted at two temperature levels (50°C and 60°C) and three load levels (705, 750 and 795 N). The air voids of the samples were calculated from the theoretical maximum specific gravity ($G_{mm}$) of the loose mixtures (obtained by softening cores) and bulk specific gravity ($G_{mb}$) of the HWTD samples prepared from the cores.

LIFEREG procedure in SAS was performed for developing accelerated testing models using HWTD test data and to test the effect of different factors on the dependent (response) variable. Not all factors were significant for all projects presumably due to lower number of data points (or lesser degrees of freedom in the statistical process). Test temperature was significant for all projects and load for one (K-4). However, the model, shown in Equation (7), was used in accelerated test data modeling based on the engineering judgment that all three factors (test temperature, load levels, and sample air voids) affect HWTD test results. Table 4 tabulates the number of wheel passes to 20-mm rut depth predicted by the models and those obtained from the HWTD tests of field cores.

Table 4: Comparison of HWTD test results and model-predicted wheel passes for field cores

| Temp. ($^0C$) | Load (N) | K-4 | | | K-258 | | | US-83 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pred. WP | Obs. WP | % Diff. | Pred. WP | Obs. WP | % Diff. | Pred. WP | Obs. WP | % Diff. |
| 50 | 705 | 19,053 | 17,290 | 9.3 | 16,667 | 14,270 | 14.4 | 29,400 | 15,210 | 48.3 |
| 50 | 750 | 16,157 | 18,015 | -12 | 16,624 | 15,420 | 7.2 | 28,375 | 18,525 | 34.7 |
| 50 | 795 | 13,563 | 15,130 | -12 | 14,385 | 10,745 | 25.3 | 19,920 | 15,065 | 24.4 |
| 60 | 705 | 5,797 | 4,855 | 16.2 | 3,563 | 2,870 | 19.5 | 5,686 | 3,145 | 44.7 |
| 60 | 750 | 4,842 | 4,585 | 5.3 | 2,675 | 3,685 | -38 | 5,580 | 3,310 | 40.7 |
| 60 | 795 | 4,004 | 3,655 | 8.7 | 2,602 | 2,445 | 6.0 | 3,426 | 2,715 | 20.8 |

Notes: WP – wheel passes; Pred. – predicted; Obs. – observed; % Diff. – percent difference.

In most cases, the number of wheel passes at a test temperature of $60^oC$ is less than or equal to 5,000 which will translate into a test duration of two hours or less.

## 8 CONCLUSIONS

Based on this study the following conclusions can be made:

1. Hamburg Wheel-Tracking Device (HWTD) test results on laboratory-compacted and core samples show that the test duration can be reduced to about two hours when higher test temperature and standard load levels are used.
2. A Weibull model for survival analysis was successfully fitted to the HWTD test results.
3. Good consistency between the accelerated testing (statistical) model-predicted and observed test results were obtained for the standard test load (705 N) and higher temperature ($60^oC$) for both laboratory-compacted samples and field cores.

## 9 ACKNOWLEDGEMENTS

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## REFERENCES

Aschenbrener, T., (1995). Evaluation *of Hamburg Wheel-Tracking Device to Predict Moisture Damage in Hot Mix Asphalt*. In Transportation Research Record 1492, TRB, National Research Council, Washington, D.C., U.S.A., pp. 193-201.

Buchanan, M. S., (1997). *An Evaluation of Laboratory Wheel-Tracking Devices*. National Asphalt Pavement Association, National Center for Asphalt Technology, Auburn, Alabama, U.S.A.

Gogula, A., Hossain, M., Boyer, J., and Romanoschi, S. (2003). *Effect of PG Binder Grade and Source on Performance of Superpave Mixtures under Hamburg Wheel Tester.* In Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, Iowa, U.S.A.

Hicks, G. R., (1991). *Moisture Damage in Asphalt Concrete*. NCHRP Report No. 175, Transportation Research Board, National Research Council, Washington D.C., U.S.A.

Izzo, R. P., and Tahmoressi, M. (1999). *Use of the Hamburg Wheel Tracking Device for Evaluating Moisture Susceptibility of Hot-Mix Asphalt*. In Transportation Research Record 1681, TRB, National Research Council, Washington, D. C., U.S.A., pp. 76-85.

Klein, J. P. and Moeschberger, M. L. (1997). *Survival Analysis Techniques for Censored and Truncated Data.* Springer, New York, U.S.A.

Lai, J. S., (1989). *Development of a Laboratory Rutting Resistance Testing Method for Asphalt Mixes.* Project No. 8717, Georgia Department of Transportation, Georgia, U.S.A.

Nelson, W. (1990). *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*. John Wiley and Sons, New York, U.S.A.

Pan, C. and White, T. D. (1999). *Conditions for Stripping Using Accelerated Testing.* Report No. FHWA/IN/JTRPB97/13, Joint Transportation Research Program, Purdue University, West Lafayette, Indiana, U.S.A.

SAS Institute Inc. (1982). *SAS User's Guide: Statistics*. Carey, North Carolina, U.S.A.

SAS Institute Inc. (2008). *SAS Online Document, Version 9.1.3,* Cary, North Carolina, U.S.A., http://support.sas.com/onlinedoc/913/docMainpage.jsp. Accessed July 28, 2008.