Pavement rutting characterization using deflection basin parameters

Kasthurirangan Gopalakrishnan* & Marshall R Thompson
Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

Received 1 May 2006; accepted 22 December 2006

The U.S. Federal Aviation Administration’s National Airport Pavement Test Facility (NAPTF) was constructed to generate full-scale traffic test data to support the development of advanced airport pavement design procedures. During the first series of traffic tests, a six-wheel Boeing 777 gear and a four-wheel Boeing 747 gear were tested on flexible pavements until they were deemed failed. Heavy Weight Deflectometer (HWD) tests were conducted prior to and throughout the traffic testing to assess the structural integrity of pavements. An inertial profiling device was used to measure the transverse surface profiles periodically during the traffic testing to monitor the development of rut depths. The NAPTF rutting data were characterized using the simple Power model. In this study, regression models were developed to obtain the rutting model parameters, in terms of rutting potential and rutting rate, as functions of initial HWD surface deflections. The results indicated that the rutting potential is strongly related to initial surface deflections. If the rutting model (Power model) coefficients can be related to HWD structural responses, a viable rutting algorithm can be developed for use in a priori airport pavement design and management activities.

IPC Code: E01C9/00

The introduction of New Generation Aircraft (NGA) such as the Boeing 777 (B777) in 1995 necessitated a fundamental need to develop new airport pavement design procedures based on sound theoretical principles and with rational models verified from full-scale test data. A joint funding provided by the United States’ (U.S.) Federal Aviation Administration (FAA) and the Boeing Company under a Cooperative Research and Development Agreement (CRDA) laid plans for the construction of the National Airport Pavement Test Facility (NAPTF). The NAPTF is located at the FAA’s William J. Hughes Technical Center, near Atlantic City International Airport, New Jersey, USA. The facility was dedicated in April 1999 and the first series of traffic tests (referred to as Construction Cycle 1 or CC1) were conducted between February 2000 and September 2001.

The NAPTF test pavement area is 274.3 m (900 ft.) long and 18.3 m (60 ft.) wide and it consists of in-situ static and dynamic pavement instrumentation and data acquisition systems. During the CC1, the NAPTF had a total of nine pavement test sections (six flexible and three rigid) built on three different subgrade materials: low-strength (target California Bearing Ratio (CBR) of 4), medium-strength (target CBR of 8), and high-strength (target CBR of 20). The naturally-occurring sandy-soil material at the NAPTF site underlies each subgrade layer. Two different base course layers were used: conventional (unbound granular material) and stabilized (asphalt concrete). In this paper, test results from two medium-strength subgrade test sections and two low-strength subgrade test sections were considered.

During the first series of traffic tests, two aircraft gear configurations, a six-wheel dual-tridem Boeing 777 (B777) landing gear in one lane and a four-wheel dual-tandem Boeing 747 (B747) landing gear in the other lane were tested simultaneously. Transverse surface profile (TSP) measurements and straightedge rut depth measurements were made at regular intervals to monitor the development of rut depths. Heavy Weight Deflectometer (HWD) tests were conducted at different times to monitor the effect of time and traffic on the pavement structural condition.

The NAPTF test sections were trafficked until failure. The primary objective of the trafficking tests was to determine the number of load applications to cause shear failure in the subgrade. According to the NAPTF failure criterion, failure is defined as the presence of at least 25.4 mm (1 in.) surface upheaval adjacent to the traffic lane. This is linked to a structural or shearing failure in the subgrade. After the

*Present address: 498 Town Engineering Building, Department of Civil Engineering, Iowa State University, Ames, IA 50011-3232, USA (E-mail: rangan@iastate.edu)
completion of NAPTF traffic testing, post-traffic trench studies were conducted to investigate the failure mechanism of the pavement structures.

In a previous study, the NAPTF flexible pavement rutting data were successfully characterized using the Power model. In this paper, the Power model coefficients, which are linked to rutting potential and rutting rate, are related to the initial surface deflections and the derived deflection basin parameters. Development of such functional relationships would enable the prediction of general pavement performance based on initial surface deflections obtained from FWD testing. More field data from full-scale tests are needed to verify/validate such response-performance relationships. If the Power model coefficients can be related to HWD structural responses, a viable rutting algorithm can be developed for use in a priori airport pavement design and management activities.

NAPTF Flexible Pavement Sections

Each NAPTF test section is identified using a three-character code (MFC, LFS, etc.), where the first character indicates the subgrade strength (L for low, M for medium, and H for high), the second character indicates the test pavement type (F for flexible and R for rigid), and third character signifies whether the base course material is conventional (C) unbound granular material or asphalt-stabilized (S). Thus, the test section LFC refers to a conventional granular base flexible pavement built over a low-strength subgrade, whereas test section MFS refers to an asphalt-stabilized base flexible pavement built over a medium-strength subgrade.

Cross-sectional views of the as-constructed NAPTF flexible test items considered in this study are shown in Fig. 1. The items P-209 granular base (crushed stone), P-154 granular sub-base (grey quarry blend fines) and P-401 (asphalt concrete) are as per standard specifications detailed in the FAA Circular No. AC 150/5370-10A. The P-401 asphalt concrete (AC) was used in the surface course as well as in the stabilized base course of MFS and LFS test sections.

A MH-CH soil classification (ASTM Unified Soil Classification System) material known as County Sand and Stone Clay (CSSC) was used for the low-strength subgrade while DuPont Clay (DPC) (CL-CH soil classification) was used for the medium-strength subgrade. The naturally occurring sand layer underlying the NAPTF subgrade layers was classified as a SW-SM soil with a target strength of 20 CBR. The NAPTF materials characterization test results are contained in the FAA’s materials database (accessible for download at the FAA Airport Technology website: www.airporttech.tc.faa.gov).

Traffic Testing

Housed within NAPTF is a 5,340 kN (1.2 million-lbs) pavement testing machine spanning two sets of railway tracks that are 23.2 m (76 ft) apart. The vehicle is equipped with six adjustable dual-wheel loading modules with a total of twelve wheels. A hydraulic system applies the load to the wheels on the modules. The twelve test wheels are capable of being configured to represent two complete landing gear trucks having from two to six wheels per truck and adjustable up to 6.1 m (20 ft) forwards and sideways. The wheel loads are adjustable to a maximum of 333.75 kN (75,000 lbs) per wheel.

During the CC1 traffic testing, a six-wheel dual-tridem gear configuration (B777) with 1,372 mm (54 in.) dual spacing and 1,448 mm (57 in.) tandem
Spacing was loaded on the north wheel track. The south side was loaded with a four-wheel dual-tandem gear configuration (B747) having 1,118 mm (44 in.) dual spacing and 1,473 mm (58 in.) tandem spacing. The NAPTF traffic test machine and test gear configurations are shown in Fig. 2. The wheel loads were set to 20.4 tonnes (45,000 lbs or 45 kips) each and the tire pressure was 1,295 kPa (188 psi). In the low-strength subgrade test sections (LFC and LFS), the wheel loads were increased from 20.4 tonnes (45 kips) to 29.4 tonnes (65 kips) after 20,000 initial load repetitions. The traffic speed was 8 km/h (5 mph) throughout the traffic test program. To realistically simulate transverse aircraft movements, a fixed wander pattern was during NAPTF traffic testing.

According to the FAA, the primary objective of the NAPTF trafficking tests was to determine the number of load applications to cause shear failure in the subgrade. Per NAPTF failure criterion, this is reflected as 25.4 mm (1 in.) surface upheaval adjacent to the traffic lane. The LFC and LFS sections showed few signs of genuine distress even after 20,000 passes and therefore the wheel loading was increased from 20.4 tonnes to 29.4 tonnes.

Non-Destructive Testing

Non-destructive tests (NDT) using both Falling Weight Deflectometer (FWD) and Heavy Weight Deflectometer (HWD) were conducted on NAPTF flexible pavement test sections at various times. This study focuses on analyzing the HWD surface deflection measurements.

The Falling Weight Deflectometer (FWD) test is one of the most widely used tests for assessing the structural integrity of pavement systems in a non-destructive manner and to determine the in-situ moduli of the pavement layers. In the case of airfield pavements, a Heavy Weight Deflectometer (HWD) test, which is similar to a FWD test, but using higher load levels, is used. Many studies have addressed the interpretation of FWD/HWD pavement deflection measurements as a tool to characterize pavement-subgrade systems.

HWD tests were conducted on the B777 and B747 trafficked lanes and on the untrafficked centerline (C/L) of NAPTF flexible test sections (see Fig. 3). The FAA HWD equipment configured with a 305 mm (12 in.) loading plate and a 27-30 ms pulse width was used for the HWD tests. The surface deflections were measured using seismometers at offsets of 0 mm ($D_0$), 305 mm ($D_1$), 610 mm ($D_2$), 914 mm ($D_3$), 1219 mm ($D_4$), and 1524 mm ($D_5$) intervals from the center of the load. Note that the deflection under the load plate ($D_0$) is an indicator of overall pavement stiffness while the deflections obtained at 914 mm or farther offsets are related to subgrade stiffness.

The HWD tests were performed at nominal force amplitudes of 53 kN (12 kip), 107 kN (24 kip), and 160 kN (36 kip). This paper focuses on the 160 kN HWD test results as they will be more representative of responses obtained under heavy aircraft gear loading. These tests were performed at approximately 3.05 m (10 ft) intervals in each flexible test section. All test data referenced in this paper are available for download on the FAA Airport Pavement Technology website. Detailed analyses of NAPTF HWD test results are presented elsewhere.

In this study, apart from the surface deflections, certain deflection basin parameters (DBPs) were also considered. Deflection basin parameters (DBPs) are...
widely used for three major applications: (i) to check the structural integrity of in-service pavements, (ii) to relate to critical pavement responses, and (iii) to calculate the in situ layer moduli of the pavements.\(^7\)

Based on a comprehensive literature review, the most widely used and effective DBPs were identified: AREA, area under pavement profile (AUPP), impact stiffness modulus (ISM), surface curvature index (SCI), base curvature index (BCI), and base damage index (BDI).

The AREA\(^8\) shape parameter defines the stiffness of the pavement structure as a shape factor. It is the partial area under the deflection basin curve (normalized with respect to \(D_0\)). The AUPP is also a deflection basin shape parameter and its definition is complimentary to the AREA parameter, i.e., lower AUPP corresponds to higher pavement stiffness and vice versa (Hill and Thompson, unpublished work/data, 1988). The ISM is computed as the ratio of FWD/HWD plate load over maximum surface deflection (\(D_0\)) and is frequently used in airport pavement evaluation.

The SCI can provide information on changes in relative strength of the near-surface layers, especially the AC layer. Based on their finite element analyses, Xu et al.\(^9\) found that for a certain thickness of the AC layer, the AC moduli and SCI values exhibit an approximately linear relationship in a log-log scale. The BCI is a subgrade condition indicator especially in aggregate base pavements and is strongly related to the subgrade modulus.\(^10,11\) The BDI is related to base layer modulus and is a critical DBP for subgrade condition evaluation in full-depth pavements. A summary of DBPs used in this study and their definitions are summarized in Table 1. In a related study, these DBPs were found to be sensitive to NAPTF pavement structural deterioration under repeated aircraft gear loading.\(^1\)

The DBP results from 160 kN HWD tests conducted in January 11, 2000 are summarized in Tables 2 and 3 for B777 traffic lane and B747 traffic lane, respectively. The AC mid-depth temperature was 8.9°C (48°F). The results are consistent with the definitions of the DBPs. The asphalt-stabilized base sections (MFS and LFS) are stiffer than the conventional granular-base sections (MFC and LFC) as indicated by relatively higher magnitudes of AREA and ISM. The opposite is true for other DBPs, i.e., relatively lower magnitudes of AUPP, SCI, BCI, and BDI for asphalt-stabilized base sections (MFS and LFS) compared to granular-base sections (MFC and LFC) which is consistent with the definitions of the DBPs. In general, the coefficients of variations (COVs) for the DBPs are higher in the case of conventional test sections (MFC and LFC). In general, both the B777 and B747 traffic lane show similar magnitudes of DBPs.

### Table 1 — Deflection basin parameters considered in this study

<table>
<thead>
<tr>
<th>Deflection Basin Parameter Formula (DBP)</th>
<th>AREA</th>
<th>AUPP</th>
<th>Impact Stiffness Modulus (ISM)</th>
<th>Surface Curvature Index (SCI)</th>
<th>Base Curvature Index (BCI)</th>
<th>Base Damage Index (BDI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA = (6(D_0 + 2D_1 + 2D_2 + D_3)/D_0)</td>
<td>AREA = ((5D_0 - 2D_1 - 2D_2 - D_3)/2)</td>
<td>ISM = Load/D_0</td>
<td>SCI = (D_0 - D_1)</td>
<td>BCI = (D_2 - D_1)</td>
<td>BDI = (D_1 - D_2)</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 — Summary of pre-traffic HWD test results (B777 traffic lane)

<table>
<thead>
<tr>
<th>DBP</th>
<th>MFC</th>
<th>LFC</th>
<th>MFS</th>
<th>LFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Std. Dev.</td>
<td>% COV</td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>AREA</td>
<td>22</td>
<td>2.5</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>AUPP</td>
<td>49</td>
<td>18.0</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>ISM</td>
<td>914</td>
<td>132</td>
<td>14</td>
<td>944</td>
</tr>
<tr>
<td>SCI</td>
<td>12.7</td>
<td>7.31</td>
<td>58</td>
<td>9.10</td>
</tr>
<tr>
<td>BCI</td>
<td>6.6</td>
<td>0.44</td>
<td>7</td>
<td>6.31</td>
</tr>
<tr>
<td>BDI</td>
<td>9.6</td>
<td>0.50</td>
<td>5</td>
<td>9.47</td>
</tr>
</tbody>
</table>
Rutting is a major distress in airport flexible pavements.\textsuperscript{12} It appears as longitudinal depressions in the wheel paths and may be accompanied by small upheavals to the sides. Permanent deformation in any or all of the pavement layers and/or subgrade under repeated traffic loading contributes to the total accumulation of pavement surface rutting.\textsuperscript{13}

During NAPTF traffic testing, transverse surface profile (TSP) measurements were made at two locations (west side – profile line 1 and east side – profile line 2) to monitor the progression of rutting in the test sections. A manually propelled inertial profiling device was used to measure the transverse surface elevation profiles. A recommended test speed of 2.0 km/h (1.24 mph) was used and the profile elevation was recorded every 250 mm (9.84 in.). The development of TSPs in MFC test section at different stages of trafficking is shown in Fig. 4.

Using the TSP measurements, for a given number of traffic load repetitions ($N$), maximum surface ruts were extracted from each traffic lane. For a given TSP, the maximum surface rut depth in a traffic lane was defined as the minimum profile elevation occurring within the width of that traffic lane (9.1 m (30 ft)). The results from NAPTF rutting study showed that the mean rut depths between the B777 and B747 gear trafficking do not differ significantly in all four flexible test sections.\textsuperscript{7} The TSP rut depth measurements (profile line 2) are plotted against $N$ in Fig. 5 for medium-strength test sections (MFC and MFS) and in Fig. 6 for low-strength test sections.

The 25.4 mm (1 in) surface upheaval NAPTF failure criterion did not yield consistent rut depths. The rut depths varied between 50-127 mm (2-5 in.) during the first series of testing. However, according to unified facilities criteria (UFC), a rut depth in excess of 25.4 mm (1 in) is considered as high severity rutting and it constitutes a significant functional failure requiring major maintenance.

### Table 3 — Summary of pre-traffic HWD test results (B747 traffic lane)

<table>
<thead>
<tr>
<th>DBP</th>
<th>AREA</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>% COV</th>
<th>AUPP (mils)</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>% COV</th>
<th>ISM (kips/in.)</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>% COV</th>
<th>SCI (mils)</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>% COV</th>
<th>BCI (mils)</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>% COV</th>
<th>BDI (mils)</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>% COV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MFC</td>
<td>22</td>
<td>0.5</td>
<td>2</td>
<td></td>
<td>24</td>
<td>0.6</td>
<td>3</td>
<td></td>
<td>1008</td>
<td>40</td>
<td>4</td>
<td>11</td>
<td>10.0</td>
<td>1.12</td>
<td>11</td>
<td></td>
<td>6.0</td>
<td>0.26</td>
<td>4</td>
<td></td>
<td>8.9</td>
<td>0.40</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>LFC</td>
<td>24</td>
<td>0.6</td>
<td>3</td>
<td></td>
<td>37</td>
<td>4.6</td>
<td>13</td>
<td></td>
<td>992</td>
<td>65</td>
<td>7</td>
<td>16</td>
<td>8.2</td>
<td>1.31</td>
<td>16</td>
<td></td>
<td>6.1</td>
<td>0.38</td>
<td>6</td>
<td></td>
<td>8.7</td>
<td>0.43</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>MFS</td>
<td>27</td>
<td>0.3</td>
<td>1</td>
<td></td>
<td>12</td>
<td>0.61</td>
<td>5</td>
<td></td>
<td>2248</td>
<td>45</td>
<td>2</td>
<td>8</td>
<td>2.6</td>
<td>0.20</td>
<td>8</td>
<td></td>
<td>2.4</td>
<td>0.05</td>
<td>2</td>
<td></td>
<td>2.7</td>
<td>0.09</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>LFS</td>
<td>28</td>
<td>0.4</td>
<td>2</td>
<td></td>
<td>12</td>
<td>0.9</td>
<td>7</td>
<td></td>
<td>1993</td>
<td>65</td>
<td>3</td>
<td>12</td>
<td>2.7</td>
<td>0.33</td>
<td>12</td>
<td></td>
<td>2.6</td>
<td>0.19</td>
<td>7</td>
<td></td>
<td>2.9</td>
<td>0.19</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 4 — Transverse surface profile measurements during NAPTF trafficking in MFC test section (profile line 1)](image1)

![Fig. 5 — Progression of total surface rutting during NAPTF trafficking (MFC and MFS)](image2)
Similarly, the ASTM Standard Test Method D 5340-98 suggests functional failure of the pavement if rut depth exceeds 25.4 mm (1 in) at a severity level of greater than 60%. After studying the U.S. Army Corps of Engineers Multiple Wheel Heavy Gear Load (MWHGL) performance test data which showed similar trends, Kelly and Thompson proposed that transfer functions in which failure is defined as dropping to a specific pavement condition index (PCI) level would be useful. Ultimately, the surface rut depths will dictate the performance of the pavement and not the surface upheaval. Therefore, appropriate criteria should be considered in addressing pavement performance. The NAPTF post-traffic trench study results revealed that the medium-strength test sections (MFC and MFS) failed at the subgrade level. However, the low-strength test sections (LFC and LFS) failed in the surface layers, signifying tire pressure or other upper layer effects, but not subgrade level failure. According to Hayhoe, full structural failure did not occur in the LFC and LFS test sections, probably because the subgrade material contained a significant amount of silt and the upper layers of the subgrade dried somewhat over the long period of time between construction and starting of traffic testing.

**Regression Models for Predicting Rutting Model Parameters**

A number of analytically-based, statistically-based, mechanistic, or mechanistic-empirical, and phenomenological models have been proposed to predict permanent deformation in asphalt concrete, granular materials, and soils. Previous research studies have shown that the Power model is an appropriate, versatile and practical approach. In a previous study, the NAPTF rutting results were characterized using the Power model. The Power model in terms of total surface rutting is expressed as follows: Rut Depth = AN^b, where N is the number of load repetitions; A and b are model coefficients. The NAPTF flexible pavement rutting results were characterized using the Power model to obtain the model parameters A and b. The rutting results were analyzed with respect to traffic gear configuration or traffic lane (B777 versus B747) and pavement structure (MFC, MFS, LFC, and LFS). More details related to the analysis of NAPTF flexible pavement rutting results can be found elsewhere.

Thus, if the Power model parameters A and b are known, then the surface rutting can be estimated. A and b represent the initial permanent deformation (intercept) and rate (slope) of permanent deformation, respectively in the Power model. Thompson and Nauman found that the subgrade stress ratio (SSR = repeated deviator stress/ultimate strength) was found to relate to the A term and is therefore a valid indicator of the rutting potential. Bejarano and Thompson conducted a statistical analysis to relate the Power model parameters with known factors that cause and/or influence permanent deformation in the subgrade. Subgrade stress levels, soil type, moisture-density conditions, strength, and subgrade break-point resilient modulus (ERi) in the bilinear model were considered. The bilinear model is a commonly used resilient modulus model for subgrade soils as it captures the stress-softening behaviour (decreasing resilient modulus at increasing stress levels) of fine-grained subgrade soils. Extensive laboratory testing data at University of Illinois showed that ERi, typically associated with a deviator stress of 41 kPa (6 psi) is a good indicator of soil’s resilient modulus and it can be used to classify fine-grained soils as being soft, medium, or stiff. The Asphalt Institute’s Thickness Design Manual MS-1 (1982) recommends ERi as the subgrade modulus input for elastic layer program (ELP) analysis. The results indicated that SSR, Ip (soil type index), and ERi are significantly related to A. A increases with SSR and decreases with Ip (soil type index), and ERi. The corresponding analysis for b indicated that clay content (soil type index) and SSR are related to this parameter. Larger b values were obtained for soils with higher clay contents. A straight-line regression equation was established between A (rut depth in

![Fig. 6 — Progression of total surface rutting during NAPTF trafficking (LFC and LFS)](image-url)
mils) and SSR based on comprehensive laboratory analysis of NAPTF subgrade soils. In this study, regression models were developed for predicting $A$ parameter based on initial 160 kN (36 kip) HWD deflection data.

A crucial link in the mechanistic-empirical (ME) design process is to relate pavement structural responses to performance through transfer functions. The most commonly used approach is to relate the structural response obtained prior to trafficking to performance measures such as the number of load repetitions to reach some failure point. The structural response could either be obtained from the field such as deflection from HWD testing or computed through a pavement structural model.

Surface deflection is a reliable pavement structural response indicator for predicting general performance. In the past, pavement surface deflections have been used as an indicator of the airport pavement life. An appealing feature of surface deflection is that it can be easily and readily measured using a NDT device such as FWD/HWD. Many highway agencies such as California Department of Transportation (DOT), the Asphalt Institute, Minnesota DOT, the U.K. Transport and Road Research Laboratory (TRRL) utilize surface deflection for designing AC overlays, predicting future performance, and considering wheel loading magnitude effects.

In a study conducted at Waterways Experiment Station (WES), a strong relation was found between elastic (or recoverable) deflection and allowable load repetitions on flexible pavements. Bush and Thompson developed a FWD-based evaluation procedure to predict the allowable F-4 aircraft load and the allowable aircraft passes for marginal flexible pavements. Garg and Marsey studied the pavement surface deflections from HWD tests and static load tests from NAPTF, but could not find a clear relationship, for the six pavement sections studied (two low-strength, two medium-strength, and two high-strength test sections) between pavement surface deflection and pavement life.

In this study, the field-measured surface deflections obtained prior to trafficking were used to relate to the NAPTF rutting characterization results. The results from HWD tests conducted on January 11, 2000 were used in this study. The AC mid-depth temperature was 8.9°C (48°F) on this date. Note that the NAPTF traffic testing began in February 2000. In developing deflection-based flexible pavement distress models, it is customary to eliminate the temperature effects by correcting the deflections to a standard reference temperature. In this study, the HWD surface deflections and the derived DBPs were corrected to a standard reference temperature of 21°C (70°F). The development of temperature correction models for NAPTF HWD data are discussed in detail by Gopalakrishnan.

Single-variable regression models for predicting $A$ parameter as a function of initial HWD deflection data are summarized in Table 4. For the sake of illustration, the $A$ values are plotted against initial HWD surface deflections ($D_0$) in Figure 7. Test sections with higher initial surface deflections showed higher rutting potentials ($A_s$). The models indicate that the DBPs are significantly related to $A$. Very good $R^2$ values were obtained with almost all DBPs except $D_3$ (HWD surface deflection measured at an offset of 914 mm from the load centre). The

Table 4 — Summary of single-variable regression models for predicting $A$

<table>
<thead>
<tr>
<th>Regression Model: $A = m_0 + m_1X$</th>
<th>$m_0$</th>
<th>$m_1$</th>
<th>$R^2$</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-18.394$</td>
<td>$D_0$ (mils)</td>
<td>$1.537$</td>
<td>$0.574$</td>
<td>$21.557$</td>
</tr>
<tr>
<td>$-47.834$</td>
<td>$D_1$ (mils)</td>
<td>$3.287$</td>
<td>$0.666$</td>
<td>$19.099$</td>
</tr>
<tr>
<td>$-82.402$</td>
<td>$D_3$ (mils)</td>
<td>$11.180$</td>
<td>$0.542$</td>
<td>$22.345$</td>
</tr>
<tr>
<td>$306.201$</td>
<td>AREA</td>
<td>$11.329$</td>
<td>$0.585$</td>
<td>$21.290$</td>
</tr>
<tr>
<td>$-1.287$</td>
<td>AUPP (mils)</td>
<td>$1.053$</td>
<td>$0.574$</td>
<td>$21.557$</td>
</tr>
<tr>
<td>$110.888$</td>
<td>ISM (kips/in.)</td>
<td>$-0.067$</td>
<td>$0.616$</td>
<td>$20.478$</td>
</tr>
<tr>
<td>$11.165$</td>
<td>SCI (mils)</td>
<td>$2.614$</td>
<td>$0.447$</td>
<td>$24.559$</td>
</tr>
<tr>
<td>$-14.186$</td>
<td>BCI (mils)</td>
<td>$8.634$</td>
<td>$0.574$</td>
<td>$21.557$</td>
</tr>
<tr>
<td>$-2.694$</td>
<td>BDI (mils)</td>
<td>$4.621$</td>
<td>$0.574$</td>
<td>$21.557$</td>
</tr>
</tbody>
</table>

Number of cases $= 7$

Power model: Rut depth (mils) = $AN^b$

![Fig. 7 — $A$ (rutting potential) versus pre-traffic HWD maximum surface deflections](image)
In this study, the pre-traffic Heavy Weight Deflectometer (HWD) surface deflections and the derived deflection basin parameters (DBPs) were related to NAPTF rutting characterization model coefficients. The HWD deflections and DBPs were corrected to a standard reference temperature of 21°C (70°F). Regression models were developed for predicting Power model parameters $A$ and $b$ based on initial 160 kN (36 kip) HWD DBPs. Almost all the DBPs considered in the analysis were significantly related to $A$ parameter (rutting potential). Regression equations for $b$ (rutting rate) developed as a function of $D_3$ show reasonable precision. More field data from full-scale tests are needed to verify the findings of this study.

If the rutting (Power) model coefficients can be related to pavement surface deflections from HWD tests, a viable rutting algorithm can be developed for use in a priori airport pavement design and management activities. The concepts, principles, and analyses presented in this paper are for the specific materials and soils used at the NAPTF. However, the approach is considered generally applicable to airport flexible pavement systems.

### Conclusions

In a mechanistic-empirical flexible pavement design procedure, the transfer functions (or distress models) are used to relate pavement structural responses (deflections, stresses and strains) determined from mechanistic structural models to pavement performance as measured by the type and severity of distress (cracking, rutting, etc.). The traffic test results from the Federal Aviation Administration’s National Airport Pavement Test Facility (NAPTF) can be used to investigate the relative effects of four- and six-wheel aircraft gear loads, and verify/develop failure criteria that can be used for the development of mechanistic based airport pavement design procedures.

During the first series of traffic tests, two aircraft gear configurations, a six-wheel dual-tridem Boeing 777 (B777) landing gear in one lane and a four-wheel dual-tandem Boeing 747 (B747) landing gear in the other lane were tested simultaneously. Transverse surface profile (TSP) measurements were made at regular intervals to monitor the development of rut depths. Heavy Weight Deflectometer (HWD) tests were conducted at different times to monitor the effect of time and traffic on the pavement structural condition. The NAPTF rut depth measurements were characterized using the Power model (Rut depth = $AN^b$; where $A$ and $b$ are model parameters). The Power model coefficient $A$ is linked to rutting potential and $b$ to rutting rate.

### Acknowledgements

This paper was prepared from a study conducted in the Center of Excellence for Airport Technology. Funding for the Center of Excellence is provided in part by the Federal Aviation Administration under Research Grant Number 95-C-001. The Center of Excellence is maintained at the University of Illinois at Urbana-Champaign that works in partnership with Northwestern University and the Federal Aviation Administration. Ms. Patricia Watts is the FAA Program Manager for Air Transportation Centers of Excellence and Dr. Satish Agarwal is the Manager of the FAA Airport Technology R & D Branch. The authors gratefully acknowledge the assistance rendered by Dr. David Brill and Dr. Gordon Hayhoe of FAA, and Dr. Navneet Garg of SRA International Inc. in conducting this study.

### Nomenclature

- MFC = a conventional granular-base flexible pavement section over a medium-strength subgrade
- MFS = an asphalt-stabilized base flexible pavement section over a medium-strength subgrade
- LFC = a conventional granular-base flexible pavement section over a low-strength subgrade

---

**Table 5 — Summary of single-variable regression models for predicting $b$**

<table>
<thead>
<tr>
<th>Regression Model: $b = m_0 + m_1X$</th>
<th>$m_0$</th>
<th>$X$</th>
<th>$m_1$</th>
<th>$R^2$</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$ (mils)</td>
<td>0.279</td>
<td>D_0 (mils)</td>
<td>0.001</td>
<td>0.018</td>
<td>0.079</td>
</tr>
<tr>
<td>$A_3$ (mils)</td>
<td>0.503</td>
<td>D_3 (mils)</td>
<td>-0.018</td>
<td>0.214</td>
<td>0.071</td>
</tr>
<tr>
<td>$A_70$ (mils)</td>
<td>0.70378</td>
<td>D_70 (mils)</td>
<td>-0.065</td>
<td>0.503</td>
<td>0.056</td>
</tr>
<tr>
<td>AREA</td>
<td>0.439</td>
<td>AREA</td>
<td>-0.006</td>
<td>0.026</td>
<td>0.079</td>
</tr>
<tr>
<td>AUPP (mils)</td>
<td>0.286</td>
<td>AUPP (mils)</td>
<td>0.0005</td>
<td>0.018</td>
<td>0.079</td>
</tr>
<tr>
<td>ISM (kips/in.)</td>
<td>0.317</td>
<td>ISM (kips/in.)</td>
<td>-1.08E-05</td>
<td>0.003</td>
<td>0.080</td>
</tr>
<tr>
<td>SCI (mils)</td>
<td>0.270</td>
<td>SCI (mils)</td>
<td>0.003</td>
<td>0.018</td>
<td>0.079</td>
</tr>
<tr>
<td>BCI (mils)</td>
<td>0.281</td>
<td>BCI (mils)</td>
<td>0.004</td>
<td>0.018</td>
<td>0.079</td>
</tr>
<tr>
<td>BDI (mils)</td>
<td>0.286</td>
<td>BDI (mils)</td>
<td>0.002</td>
<td>0.018</td>
<td>0.079</td>
</tr>
</tbody>
</table>

Number of cases = 7

Power model: Rut depth (mils) = $AN^b$
LFS = an asphalt-stabilized base flexible pavement section over a low-strength subgrade
B777 = Boeing 777
B747 = Boeing 747
N = number of load repetitions
HWD = Heavy Weight Deflectometer
D0 = pavement surface deflection under center of HWD loading plate
D1 = pavement surface deflection at 305 mm (12 in.) under center of HWD loading plate
D2 = pavement surface deflection at 610 mm (24 in.) under center of HWD loading plate
D3 = pavement surface deflection at 914 mm (36 in.) under center of HWD loading plate
D4 = pavement surface deflection at 1219 mm (48 in.) under center of HWD loading plate
D5 = pavement surface deflection at 1524 mm (60 in.) under center of HWD loading plate
D6 = pavement surface deflection at 1829 mm (72 in.) under center of HWD loading plate
DBP = deflection basin parameter
AUPP = area under pavement profile
ISM = impact stiffness modulus
SCI = surface curvature index
BCI = base curvature index
BDI = base damage index;
A = Power model (rut depth = ANb) parameter (linked to rutting potential)
b = Power model (rut depth = ANb) parameter (linked to rutting rate)

References
21 Bejarano M & Thompson M R, Subgrade soil evaluation for the design of airport flexible pavements, FAA COE Report No. 8, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA, 1999.
26 Garg N & Marsey W H, Comparison between falling weight deflectometer and static deflection measurements on flexible pavements at the national airport pavement test facility (NAPTF), paper presented at the Federal Aviation Administration Airport Technology Transfer Conf, Chicago, IL, USA, 2002.