



PREDICTING CAPACITIES OF RUNWAYS SERVING NEW LARGE AIRCRAFT

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Abstract. This paper presents a simplified approach for predicting the allowable load repetitions of New Large Aircraft (NLA) loading for airfield runways based on Non-Destructive Test (NDT) data. Full-scale traffic test results from the Federal Aviation Administration's National Airport Pavement Test Facility (NAPTF) were used to develop the NDT-based evaluation methodology. Four flexible test pavement sections with variable (unbound layer) thicknesses were trafficked using six-wheel and four-wheel NLA test gears until the test pavements were deemed failed. Non-destructive tests using a Heavy Weight Deflectometer (HWD) were conducted prior to the initiation of traffic testing to measure the pavement surface deflections. In the past, pavement surface deflections have been successfully used as an indicator of airport pavement life. In this study, the HWD surface deflections and the derived Deflection Basin Parameters (DBPs) were related to functional performance of NAPTF flexible pavements through simple regression analysis. The results demonstrated the usefulness of NDT data for predicting the performance of airport flexible pavements serving the next generation of aircrafts.

Keywords: new generation aircraft, National Airport Pavement Test Facility (NAPTF), heavy weight deflectometer (HWD), surface deflection, airport flexible pavement, rutting.

1. Introduction

The impact of New Large Aircraft (NLA), such as the Boeing 777 aircraft, on existing and new airport pavements is an important issue facing the aviation industry today. Following Russia's Antonov AN 225, the world's largest aircraft, McDonnell Douglas, Boeing and Airbus Industrie are all developing NLA comparable in size to the Antonov. The increased wheel loads, higher tire pressures and complex landing gear configurations of the NLA have generated widespread concern about their impact on airport pavement life and performance and about their suitability for use in airports. Recognizing this issue, the U.S. Federal Aviation Administration's (FAA's) National Airport Pavement Test Facility (NAPTF) was constructed to generate full-scale test data needed to verify/develop advanced airport pavement thickness design procedures. The NAPTF is located near Atlantic City International Airport, New Jersey.

In a recent series of traffic tests conducted at NAPTF, four flexible pavement sections with variable granular subbase thicknesses (referred to as Construction Cycle 3 or CC3) were subjected to repeated loading of six-wheel and four-wheel New Large Aircraft (NLA) landing gears until the pavement sections were deemed failed. The

CC3 traffic testing was started on September 3, 2002 and was completed by October 18, 2002.

The four flexible pavement sections (LFC1, LFC2, LFC3, and LFC4) were constructed over a low-strength subgrade (target California Bearing Ratio [CBR] of 3) which already existed from a previous construction cycle (Construction Cycle 1 or CC1). The label "LFC*" refers to a conventional granular-base pavement built over a low-strength subgrade. By Hayhoe (2004), the design lives of the CC3 pavement test items varied from 200 to 36,000 passes based on structural analysis using the FAA's layered elastic airport pavement design program, LEDFAA. The LFC1 test section was 12.2-m (40-ft) long and LFC4 was 24.4-m (80-ft) long while both LFC2 and LFC3 spanned 18.3 m (60 ft) each.

Cross-sectional views of as-constructed CC3 flexible test sections are shown in Fig. 1. The items P-209 base (crushed rock), P-154 subbase (gray quarry blend fines) and P-401 Asphalt Concrete (AC) used in the construction of test items are as per standard specifications detailed in the FAA Circular No. AC 150/5370-10A. 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. The naturally-occurring sandy-soil material (SW-SM soil classification) at

the NAPTF site underlies each subgrade layer. The NAPTF materials characterization test results are stored in a database which is available for download or direct access on the FAA Airport Pavement Technology Website. Research, presented by Hayhoe, Garg (2001).

LFC1		LFC2		LFC3		LFC4	
P-401 AC surface	127 mm	P-401 AC surface	127 mm	P-401 AC surface	127 mm	P-401 AC surface	127 mm
P-209 granular base	203 mm	P-209 granular base	203 mm	P-209 granular base	203 mm	P-209 granular base	203 mm
P-154 granular subbase	406 mm	P-154 granular subbase	610 mm	P-154 granular subbase	864 mm	P-154 granular subbase	1092 mm
LOW strength controlled subgrade		LOW strength controlled subgrade		LOW strength controlled subgrade		LOW strength controlled subgrade	

Fig. 1. Cross-sections of as-constructed NAPTF flexible test sections

Non-destructive tests (NDTs) using a Heavy Weight Deflectometer (HWD) were conducted prior to traffic testing to evaluate the uniformity of the test sections. During traffic testing, Transverse Surface Profile (TSP) measurements as well as straightedge rut depth measurements were made at frequent intervals to monitor the progression of pavement rutting. In the past, pavement surface deflections have been successfully used as an indicator of airport pavement life. This paper describes the development of a HWD-based evaluation procedure to predict the allowable NLA gear passes for airport flexible pavements. Although, the results are applicable specifically for the six-wheel and four-wheel NLA gears used at NAPTF, the methodology can be easily extended to prototype NLA gear loading with additional data from such full-scale traffic tests. The pavement rutting performance (capacity) was defined in terms of number of load repetitions to reach specific rut depth levels based on well-known pavement distress criteria.

2. Non-destructive tests

By Chan *et al.* (1993), Holt *et al.* (2002) and Gopalakrishnan and Thomson (2005), the HWD is a heavier loading Falling Weight Deflectometer (FWD), and is commonly used to test the structural integrity of airport pavements non-destructively. The HWD measures pavement surface response (i.e., deflections) from an applied dynamic load that simulates a moving wheel of an aircraft at moderate speeds. Studies by Bush and Baladi (1989) and Tayabji, Lukanen (2000) have addressed the interpretation of pavement surface deflection measurements using FWD/HWD as a tool to characterize pavement-subgrade systems. The deflection data that are collected with the HWD equipment can provide both qualitative and quantitative data about the strength of a pavement at the time of testing, see FAA Advisory Circular (2004).

At the NAPTF, HWD tests were conducted on August 27, 2002 to evaluate the uniformity of the CC3 flexible test sections. The HWD tests were conducted using a KUAB 2m HWD device acquired by the FAA. The FAA HWD equipment operates on the principle of dropping weights on a series of hard, rubber buffers separated by a

second series of weights and buffers which are connected to a loading plate resting on the pavement surface. These two mass systems results in a consistent and uniform, half-wave sine curve for the loading pulse. The loading plate is segmented into quarters to ensure that the loading force is evenly distributed. Weights and buffers can be added, or removed as necessary, to adjust peak load and loading time. The loading pulse shape is also influenced by the combination of weights and buffers utilized. By Guo, Marsey (2001), the drop heights can be adjusted to control the peak load.

The FAA HWD equipment was configured with a 305-mm (12-in.) loading plate and a 27-30 msec pulse width was used during testing, this presented by Guo, Marsey (2001) and McQueen *et al.* (2001). HWD tests were performed at nominal force amplitudes of 53-kN (12,000-lb), 106-kN (24,000-lb), and 160-kN (36,000-lb). This study focused on the 160-kN (36,000-lb) HWD test results.

During HWD testing, the AC pavement temperature was 25.5 °C (78 °F). The HWD test locations in each pavement test section are illustrated in Fig. 2. During traffic testing, the six-wheel traffic gear was centered on LANE 2 (north side) and the four-wheel traffic gear on LANE 5 (south side). The surface deflections were measured with seven geophones spaced at 30.5-cm (12-in.) intervals (D_0 to D_6) starting with the load center: 0 mm (D_0), 305 mm (D_1), 610 mm (D_2), 914 mm (D_3), 1 219 mm (D_4), 1 524 mm (D_5), and 1 830 mm (D_6). The HWD test sequences were repeated at 3-m (10-ft) intervals along the test lanes as shown in Fig. 2.

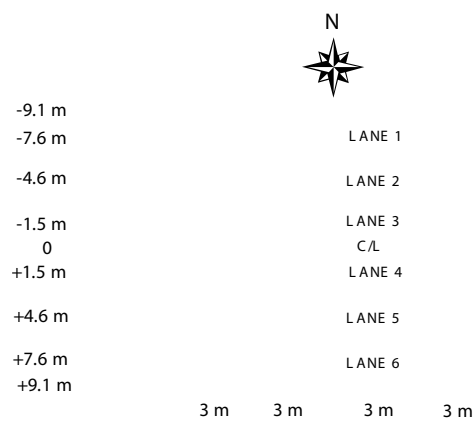


Fig. 2. Schematic diagram of Heavy Weight Deflectometer (HWD) test locations

3. Analysis of non-destructive test data

A distinctive feature of the CC3 flexible test sections is that the P-154 granular subbase thickness is the only structural variable and thus, the exclusive effect of granular subbase thickness on response and performance of these test sections can be studied. The representative pavement surface deflection basins obtained with 160-kN (36,000-lb) HWD loading are compared in figure 3 for all four test sections. The maximum surface deflection D_0 is generally a function of the loading plate, applied load, and the pavement structure as a whole

whereas the deflections at farther offsets from the load center (D_3 and greater) are predominantly governed by the subgrade properties.

The influence of subbase thickness is clearly reflected in the maximum surface deflections (D_0) (see Fig. 3). As the subbase thickness increased from 610 mm (24 in.) in LFC2 to 864 mm (34 in.) in LFC3 (difference of 254 mm), the D_0 decreased from 2.7 mm (105 mils) to 2.0 mm (80 mils) (difference of 0.7 mm). Whereas, for an increase of 228 mm (9 in.) in subbase thickness from LFC3 to LFC4, the corresponding difference in deflection was only 0.24 mm (9 mils).

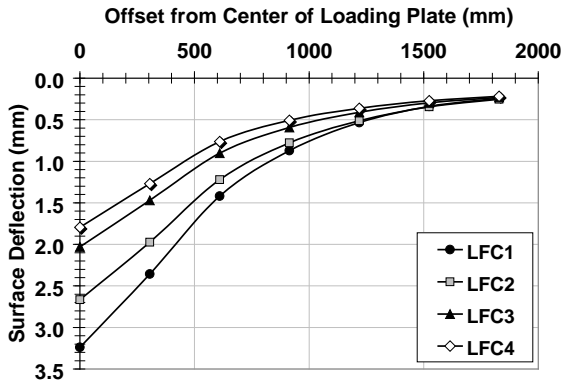


Fig. 3. HWD surface deflection basins at a sample test location at zero-traffic repetitions

In this study, apart from the surface deflections, certain Deflection Basin Parameters (DBPs) were also considered. Deflection basin parameters (DBPs), by Hossain, Zaniewski (1991), are widely used for three major applications: (a) to check the structural integrity of in-service pavements, (b) to relate to critical pavement responses, and (c) to calculate the in situ layer moduli of the pavements. 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 shape parameter defines the stiffness of the pavement structure as a shape factor, investigated by Hoffman, Thompson (1982). 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 by Hill, Thompson (1989). 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 by Bush, Thompson (1990).

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.* (2001) 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 by Horak (1987) and Kilaeski, Anani (1982). The BDI is related to base layer modulus and is a critical DBP for subgrade condition evaluation in full-depth pavements. Based on HWD deflection basins collected at frequent intervals during NAPTF trafficking on the CC1 flexible pavement test sections, Gopalakrishnan, Thompson (2005) concluded that these DBPs are effective in characterizing the structural degradation in flexible airport pavements.

A summary of DBPs used in this study and their definitions are summarized in Table 1. In Fig. 4, the DBP values obtained for each test section are compared. The differences in magnitudes between LANE 2 (6-wheel traffic lane) and LANE 5 (4-wheel traffic lane) values are not significant. The ISM and AREA values calculated along the length of the CC3 test pavement are displayed in Fig. 5.

Table 1. Deflection basin parameters considered in this study

DBP	Formula
AREA	$\frac{6(D_0 + 2D_1 + 2D_2 + D_3)}{D_0}$
AUPP	$\frac{5D_0 - 2D_1 - 2D_2 - D_3}{2}$
ISM	$\frac{P}{D_0}$
SCI	$D_0 - D_1$
BCI	$D_2 - D_3$
BDI	$D_1 - D_2$

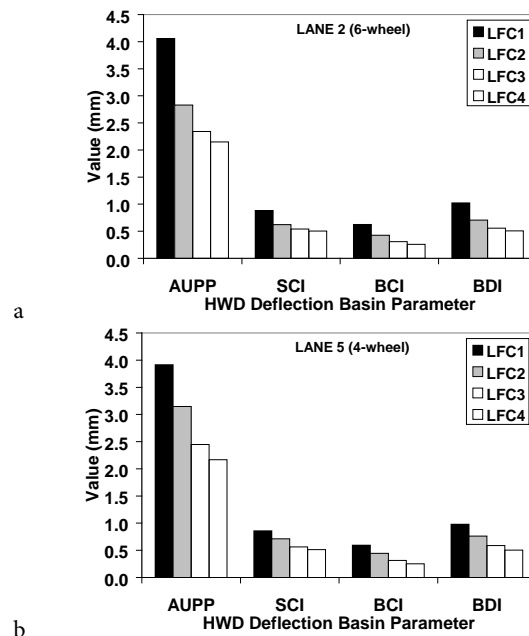


Fig. 4. Comparison of deflection basin parameters: a - LANE 2; b - LANE 5

4. NAPTF traffic testing

The CC3 test sections were trafficked using a test vehicle with a six-wheel (dual-tridem) aircraft gear (resembling Boeing 777 landing gear) on the north side traffic path (LANE 2 in Fig. 2) and a four-wheel (dual-tandem) aircraft gear on the south side (LANE 5 in Fig. 2). The gear configuration details for the test gears are shown in Fig. 6. The wheel load was set to 25 tonnes (55,000-lbs) and the tire inflation pressure was 1,688 kPa (245 psi). The traffic speed was set to 8 km/h (5 mph). The traffic tests were conducted during September and October of 2002, immediately after construction of the test sections.

To realistically simulate transverse aircraft movements, a wander pattern consisting of a fixed sequence of 66 vehicle passes (33 traveling in the east direction and 33 traveling in the west direction), arranged in nine equally spaced wander positions (or tracks) at intervals of 260 mm

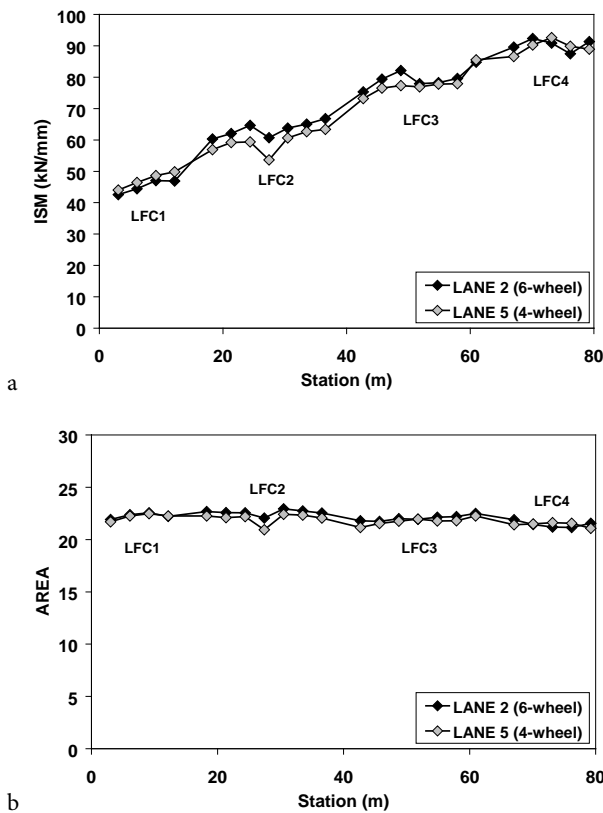


Fig. 5. Variability in deflection basin parameters along test pavement: a – Impact Stiffness Modulus (ISM); b – AREA

6-wheel Gear	4-wheel Gear
1372 mm	1372 mm
1448 mm	1448 mm
1448 mm	

Fig. 6. Traffic test gear configuration details

(10.25 in.), was used during the traffic testing. This wander pattern simulates a normal distribution of aircraft traffic with a standard deviation (σ) of 775 mm (30.5 in) that is typical of multiple gear passes in airport taxiways.

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, adopted from the U.S. Army Corps of Engineers multiple-wheel heavy gear load tests conducted at Vicksburg, Mississippi, this is reflected as 25.4-mm (1-in.) surface upheaval adjacent to the traffic lane, see investigation by Ahlvin *et al.* (1971).

It is important to note that in the 25.4-mm (1-in.) surface upheaval failure criterion, there is no limit on the maximum rut depth. Thus, a surface upheaval of 25.4-mm (1-in.) may be accompanied by a 13-mm (0.5-in.) rut depth or rut depths in excess of 50 to 75 mm (2 to 3 in.) with no limit on the maximum allowable rut depth. However, according to the Unified Facilities Criteria (UFC), rut depths in excess of 25.4 mm (1 in.) is considered as “High” severity rutting and it constitutes a significant functional failure requiring major maintenance activities. This presented in US COE (2001).

5. Pavement performance

To monitor the progression of rutting in NAPTF test sections, Transverse Surface Profile (TSP) measurements as well as rut depth measurements using a 3.66 m- (12 ft-long straightedge) were made throughout the traffic testing. The rutting results based on TSP measurements are discussed in this paper. A non-contact laser profiling device with a span of 6.5 m (21.5 ft) and a range of 20.3 cm (8 in.) was used to measure profiles at three locations (east, west, and center) within each test item.

As mentioned previously, the CC3 traffic tests began on September 3, 2002 and ended on October 18, 2002. Pavement temperatures in the AC layer were monitored using Omega Thermistor temperature gages throughout the traffic testing. The variation in P-401 AC layer mid-depth temperature during traffic testing is shown in Fig. 7. It was found that the AC temperatures did not vary with test sections (as NAPTF is an indoor test facility) and therefore the average values obtained from all four test sections are plotted.

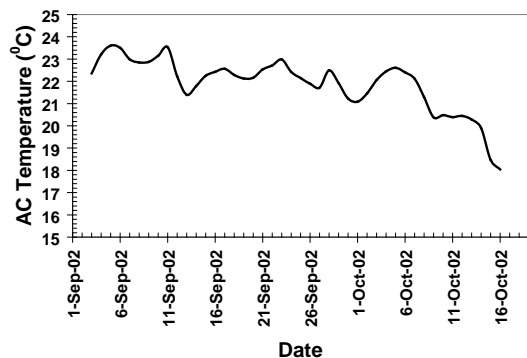


Fig. 7. Variations in asphalt concrete (AC) pavement temperature during NAPTF traffic testing

The LFC1 section showed rapid accumulation of rutting and failed at 90 passes on the 6-wheel traffic path and at 132 passes on the 4-wheel traffic path as per NAPTF failure criterion. In LFC2, the 6-wheel traffic lane reached failure at 1,100 passes, while the 4-wheel traffic lane failed at around 3,000 passes. In both LFC3 and LFC4, the traffic wheel load magnitude was increased from 25 tonnes (55 kip) to 29.5 tonnes (65 kip) after 4000 passes to accelerate failure. The 6-wheel traffic lane of LFC3 failed at 21,000 passes and trafficking was terminated on LFC4 at 23,000 passes.

The magnitudes of rut depths at failure in LFC1 and LFC2 sections were approximately 102 mm (4 in.) and 203 mm (8 in.), respectively. At the termination of traffic testing, the rut depths in the LFC3 and LFC4 sections were approximately 203 mm (8 in.) and 152 mm (6 in.), respectively by Gopalakrishnan (2004). The development of surface rutting in the NAPTF test sections under repeated traffic loading is displayed in Fig. 8. Note that the traffic wheel load magnitude was increased from 25 tonnes (55 kip) to 29.5 tonnes (65 kip) in LFC3 and LFC4 sections at 4000 passes as shown in the Fig. Using the maximum surface rut depths obtained from the TSPs, rutting analyses were performed by applying the Power model, presented by Monismith *et al.* (1975) and the pavement surface rutting rate model, presented by Gopalakrishnan (2004). The results of rutting analyses by Gopalakrishnan, Thompson (2006) are discussed in detail elsewhere.

After the completion of traffic testing, trench studies were conducted on LFC1 and LFC2 sections. Trench studies revealed that in both the sections, rutting occurred pre-dominantly in P-209 base and P-154 subbase layers. Trench studies were not conducted on LFC3 and

LFC4 test sections. The CBR values, computed as the average of the measurements from acceptance surface, trench surface, and trench pits at 30.5 cm (12 in.) and 61 cm (24 in.) from the surface of the subgrade, were approximately 4.0 for both LFC1 and LFC2, see investigation by Hayhoe (2004).

6. Estimate of performance using non-destructive test data

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 considered to reflect structural failure in the subgrade. However, as noted earlier, this failure criterion is not consistent with respect to rut depths. The CC1 trafficking results, by Gopalakrishnan (2004), showed that the NAPTF failure criterion did not yield consistent rut depths. The rut depths varied between 50.8 to 127 mm (2 to 5 in.) during CC1 traffic tests.

Ultimately, the surface rut depths will dictate the performance of the pavement and not the surface upheaval. In this study, the performance measure was defined in terms of number of wheel load repetitions to reach rut depth levels of 12.7 mm (0.5 in.), 25.4 mm (1 in.), 38.1 mm (1.5 in.), etc. Performance criteria of this type based on functional failure will limit the total surface rutting and ensure stable rutting performance. This approach, by Gopalakrishnan, Thompson (2007), was successfully used in developing response-performance relations based on CC1 trafficking data.

In CC3 test sections, rutting accumulated rapidly under trafficking and the rut depths exceeded 25.4-mm (1-in.) in fewer than 50 passes in the LFC1 and LFC2 sections. Therefore, it is not feasible to consider 25.4-mm (1-in.) rut depth level or lower in relating structural responses to rutting performance based on functional failure criteria. In this study, 38.1-mm (1.5-in.) and 50.8-mm (2-in.) rut depth levels were considered.

Surface deflection has been shown to be a reliable pavement structural response indicator for predicting general performance, see NCHRP Project (1990). The pavement surface deflections are easily measurable (using a non-destructive test device such as HWD) compared to other responses, such as stresses and strains, and are the basic response of the pavement structure to the applied load, see Garg, Marsey (2002) investigation. Many highway agencies such as California Department of Transportation (DOT), the Asphalt Institute, Minnesota DOT, the Transport Road Research Laboratory (TRRL) utilize surface deflection for designing AC overlays, predicting future performance, and considering wheel loading magnitude effects, see NCHRP Project (1990).

In a study by Ahlvin (1991) conducted at Waterways Experiment Station (WES), a strong relation was found between elastic (or recoverable) deflection and allowable load repetitions on flexible pavements. Bush, Thompson (1990) developed a FWD-based evaluation procedure to predict the allowable F-4 aircraft load and the allowable aircraft passes for marginal flexible pavements. Analysis of NAPTF

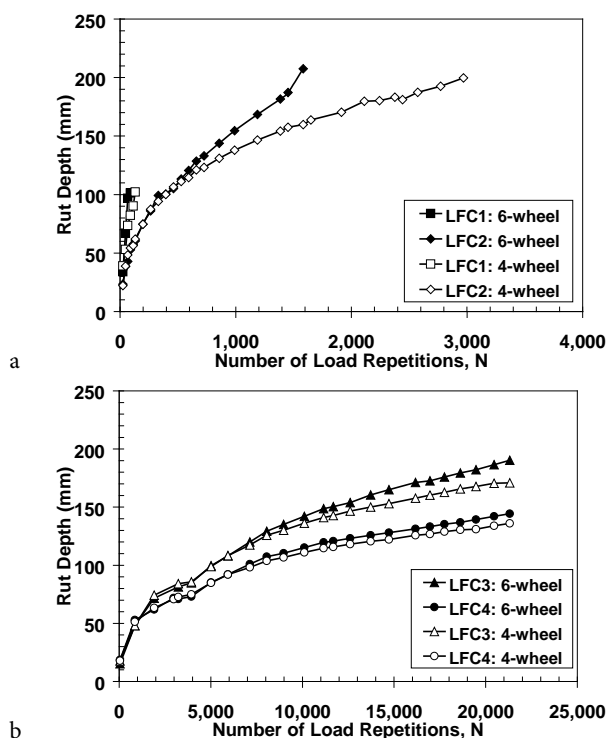


Fig. 8. Development of surface rutting with trafficking

CC1 trafficking data showed that the rutting performance of flexible test sections (defined in terms of number of load repetitions to reach specific rut depth levels) is related to initial HWD surface deflection basin parameters.

In this study, regression analyses were conducted to predict the number of load repetitions to functional failure (N_{RD}) as a function of initial 160-kN (36,000-lb) HWD responses. The results of regression analyses are summarized in Tables 2 and 3, for rut depth levels of 38.1-mm (1.5-in.) and 50.8-mm (2-in.) respectively. A total of 8 cases (4 test sections \times 2 test gears/HWD test lanes) were considered in establishing the regression models. Note that the average AC temperature at the time of CC3 HWD testing was 25.5 °C (78 °F). The surface deflections and DBPs could not be corrected to a standard reference temperature of 21.1 °C (70 °F) as there were not sufficient data to establish temperature correction equations.

Among the DBPs, D_3 , ISM, BCI and D_0 showed stronger correlations with the number of load repetitions to reach functional failure. Among these, D_3 showed the strongest correlation. Note that D_3 , surface deflection measured at an offset of 914 mm (36 in.) from the center of HWD plate, is considered to reflect the subgrade properties. All the R^2 values were statistically significant at the 99 % probability level. These results indicate the

Table 2. Summary of regression prediction models for number of load repetitions to 38.1-mm (1.5-in) rut depth

Regression model: $\log(N_{1.5}) = A + bX$				
A	X	b	R^2	Standard Error of Estimate (SEE)
5.230	D_0 (mm)	-1.181	0.961	0.153
5.190	AUPP (mm)	-0.988	0.913	0.229
-0.624	ISM (kN/mm)	0.0430	0.984	0.098
5.605	D_3 (mm)	-4.675	0.997	0.042
5.340	SCI (mm)	-4.570	0.878	0.272
4.625	BCI (mm)	-5.772	0.973	0.129
5.063	BDI (mm)	-3.905	0.938	0.193

Table 3. Summary of regression prediction models for number of load repetitions to 38.1-mm (1.5-in) rut depth

Regression model: $\log(N_{1.5}) = A + bX$				
A	X	b	R^2	Standard Error of Estimate (SEE)
6.016	D_0 (mm)	-1.384	0.879	0.332
5.928	AUPP (mm)	-1.144	0.815	0.411
-0.877	ISM (kN/mm)	0.0509	0.916	0.277
6.533	D_3 (mm)	-5.592	0.949	0.215
6.073	SCI (mm)	-5.246	0.769	0.459
5.323	BCI (mm)	-6.807	0.900	0.302
5.804	BDI (mm)	-4.553	0.849	0.371

usefulness of HWD surface deflections in developing deflection-based airport pavement rutting failure criteria.

7. Summary and conclusions

In the past, pavement surface deflections have been successfully used as an indicator of airport pavement life. In this study, the pavement surface deflections measured prior to trafficking were related to rutting performance of four flexible pavement test sections at the FAA's National Airport Pavement Test Facility (NAPTF). A simplified approach for predicting the allowable load repetitions of New Large Aircraft (NLA) loading for airport flexible pavements based on Non-Destructive Test (NDT) data was developed.

Traffic testing were conducted on four flexible test sections, with variable (unbound layer) thicknesses, using a six-wheel aircraft landing gear on one lane and a four-wheel aircraft landing gear on another lane until the test sections were deemed failed. Heavy Weight Deflectometer (HWD) tests were conducted prior to trafficking to measure the pavement surface deflections. Transverse surface profile measurements were made at frequent intervals throughout the traffic testing to monitor the progression of surface rut depths. The following conclusions are drawn from this study:

1. The NAPTF structural failure criterion did not yield consistent rut depths as the criterion is based on the magnitude of surface upheaval and there is no limit on the maximum allowable rut depth.
2. A functional failure criterion was defined based on the number of load repetitions to reach specific rut depth levels: 25.4 mm (1 in.), 38.1 mm (1.5 in.), 50.8 mm (2.0 in.), etc. Performance criteria of this type will limit the total surface rutting and ensure stable rutting performance.
3. The initial HWD surface deflections and the derived Deflection Basin Parameters (DBPs) were related to NAPTF rutting performance in terms of functional failure criteria through regression analysis.
4. These results indicate the usefulness of HWD surface deflections in developing deflection-based airport pavement rutting failure criteria and for predicting the pavement performance of airport flexible pavements serving the next generation of aircrafts.
5. Although, these results are applicable specifically for the six-wheel and four-wheel NLA gears used at NAPTF, the methodology can be easily extended to prototype NLA gear loading with additional data from such full-scale traffic tests.

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