RUTTING STUDY OF NAPTF FLEXIBLE PAVEMENT TEST SECTIONS

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Abstract

The National Airport Pavement Test Facility (NAPTF) was constructed to generate full-scale testing data to support the investigation of the performance of airport pavements subjected to complex gear loading configurations of new generation aircraft (NGA). The objectives of the NAPTF traffic/performance test program were to explore gear configuration/load and wander effects on pavement responses and performance as a function of number of load applications (N). Two gear configurations, a six-wheel tridem landing gear (B777) in one lane and a four-wheel dual-tandem landing gear (B747) 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 depth (RD). Using these measurements, a rutting study of the NAPTF flexible test sections was conducted. Statistical tests were performed to consider any difference in mean rut depths between B777 trafficking and B747 trafficking. The rut data were analyzed using the most common surface rutting models (the power model and the third-order polynomial model) and the models were compared.

The results showed that the maximum surface rut at the termination of test trafficking is higher for conventional-base flexible test items than for stabilized-base flexible test items. From an engineering standpoint, the mean rut depths accumulated under B777 loading and B747 loading were similar. The number of passes required by the B777 and B747 gears in order to reach a 25.4-mm (1-inch) rut depth was similar. The power model was statistically significant at the 99% probability level for all of the sections. The third-order polynomial rutting model is a good curve-fitting model, but its engineering significance is questionable. The rutting rate (RD/N) exhibits a linear relation with the number of load repetitions on a log-log scale.

KEY WORDS: airport pavement, rutting, transverse surface profile, straightedge, B777, B747

Introduction

The National Airport Pavement Test Facility (NAPTF) located at the Federal Aviation Administration (FAA) William J. Hughes Technical Center, Atlantic City

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International Airport, New Jersey was constructed to generate full-scale testing data to support the investigation of the performance of airport pavements subjected to complex gear loading configurations of new generation aircraft (NGA) such as the Boeing 777.

The test pavement area is 274.3 m (900 feet) long and 18.3 m (60 feet) wide. The first set of test pavements included a total of nine test sections (six flexible and three rigid) built on three different subgrade materials: low-strength (target CBR of 4), medium-strength (target CBR of 8), and high-strength (target CBR of 20). Two different base sections were used: conventional (granular) and stabilized (asphalt concrete). A plan view of the NAPTF test sections is shown in Figure 1.

Each NAPTF test section is identified using a three-character code. 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 material is conventional (C) or stabilized (S). For example, the test section MFC refers to a conventional-base flexible pavement built over a medium-strength subgrade, whereas test section LFS refers to a stabilized-base flexible pavement built over a low-strength subgrade. Cross-sectional views of the "as-built" NAPTF flexible test items are shown in Figure 2.

The NAPTF pavement testing was conducted in two phases: a response test program and a traffic test program. The objectives of the traffic test program were to explore gear configuration/load and wander effects on pavement responses (stresses, strains, and deflections) by monitoring pavement responses and performance (rutting and cracking) as a function of number of load repetitions (N). Two gear configurations, a six-wheel tridem landing gear (B777) in one lane and a four-wheel dual-tandem landing gear (B747) in the other lane were tested simultaneously.

Sensor installation included Multi-Depth Deflectometers (MDDs) and Pressure Cells (PCs) to capture critical pavement responses under traffic loading. Rutting was monitored throughout the traffic test program by transverse surface profile (TSP) measurements and straightedge rut depth measurements. This paper presents and discusses the results of analyzing the rut depths measured in NAPTF flexible test sections during traffic testing. All data referenced in this paper are accessible from the FAA AAR-410 website http://www.airporttech.tc.faa.gov.

NAPTF Material Properties

The physical properties of all of the materials used in the NAPTF test items were measured before, during and after construction for three purposes: construction quality control (QC), construction acceptance, and material characterization (Hayhoe and Garg 2001). The measured pavement material properties are available in the form of a database for download on the FAA Airport Pavement Technology web site: http://www.airporttech.tc.faa.gov. Tests were also conducted at the University of Illinois' Advanced Transportation Engineering Laboratory (U of I ATREL) to characterize these materials.

NAPTF Traffic Testing

A six-wheel dual-tridem gear configuration (B777) with 1,372-mm (54-inch) dual spacing and 1,448-mm (57-inch) tandem spacing was loaded on the North wheel track (LANE 2) while the South side (LANE 5) was loaded with a four-wheel dual-tandem gear configuration (B747) having 1,118-mm (44-inch) dual spacing and 1,473-mm (58-inch) tandem spacing. The wheel loads were set to 20.4 tonnes (45,000 lbs) each and the tire pressure (cold) was 1,295 Kpa (188 psi). In the LFC and LFS test sections, the wheel loads were increased from 20.4 tonnes (45,000 lbs) to 29.4 tonnes (65,000 lbs) after 20,000 initial load repetitions. The traffic speed was 8 km/h (5 mph) throughout the traffic test program.

Traffic Wander

To realistically simulate transverse aircraft movements, a wander pattern (see Figure 3) consisting of a fixed sequence of 66 vehicle passes (33 traveling East and 33 traveling West), arranged in nine equally spaced wander positions (or tracks) at intervals of 260 mm (10.25 inches), was used during traffic testing. This wander pattern simulates a normal distribution of aircraft traffic with a standard deviation (σ) of 775 mm (30.5 inches) that is typical of multiple gear passes in airport taxiways. As shown in the Figure, among the nine different Track Nos. (-4 to +4) over the centerline of gear passes, the North Side Track Nos. (-4 to 0) are for the B777 trafficking and the South Side Track Nos. (0 to +4) correspond to B747 trafficking. To minimize the interaction of gear loads at the subgrade level, the two gears moved in phase, with both gears moving left and right together rather than towards and away from each other.

Failure Criterion

The NAPTF 'failure' criterion, based on the criterion used by the US Corps of Engineers' Multiple Wheel Heavy Gear Load (MWHGL) Tests (Ahlvin et al 1971), is *at least 25.4 mm (1 inch) surface upheaval adjacent to the traffic lane.* This is supposed to reflect structural or shearing failure in the subgrade. During the MWHGL tests, the pavements were considered failed when either of the following conditions occurred: (a) surface upheaval of 25.4 mm (1 inch) or more of the pavement adjacent to the traffic lane, (b) severe surface cracking to the point where the pavement was no longer waterproof.

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

Except for the high-strength (HFC and HFS) test sections, which are not considered in this paper, trafficking continued until the individual pavement test sections were considered as 'failed'. The number of passes to 'failure' is summarized in Table 1 for each flexible test section.

NAPTF Rutting Study

Rutting is the load-induced permanent deformation of a flexible pavement caused by a combination of densification and shear-related deformation (White et al. 2002). Rutting in paving materials develop gradually with an increasing number of load applications, usually appearing as longitudinal depressions in the wheel paths accompanied by small upheavals to the sides (Sousa et al. 1991). 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.

Transverse surface profile (TSP) measurements as well as rut depth measurements using a 3.66 m- (12 foot-) long straightedge were made throughout the traffic testing. Several rutting studies have identified the benefits of transverse surface profile (TSP) measurements. Recently, White et al. (2002) proposed a method (for highway pavements) of estimating the contribution of individual pavement layers to rutting from analysis of TSPs.

Transverse Surface Profile (TSP) Measurements

A manually propelled inertial profiling device, CSC Digital Profilite 300 Profilair, 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 once every 250 mm (9.84 inches). In each test item, TSPs were measured along two main profile lines (Profile Line 1 and 2) marked across the pavement. In flexible test items, these two profile lines were at the one-third points along the test items about 152 mm (6 inches) to the West side of the Multi-Depth Deflectometers (MDDs). In Figure 4, the location of the main profile lines with respect to the MDD instrumentation and the location of traffic lanes together with test gear configurations are shown. All profiles were measured in the North-to-South direction. During data processing it was ensured that the final profile extends only across the 18.3-m (60-foot) width of the test pavement.

Using the TSP measurements, for a given number of 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 mm [30 ft.]).

Low-Strength Sections

The TSPs measured along profile lines 1 and 2 at specific number of load repetitions (N) are plotted in Figure 5 and Figure 6 for the low-strength flexible test sections (LFC and LFS). In the case of LFC1- profile line 1 in LFC test section and LFC2 – profile line 2 in LFC test section, the TSPs are similar and exhibit significant upheaval outside the wheel paths at the termination of test trafficking (N = 44,095) (see Figure 5). The maximum surface rut at the termination of test trafficking is about

76.2 mm (3 inches) in both B 777 and B 747 wheel paths. Similarly, the TSPs compare well between LFS1 (Figure 6) and LFS2 (Figure 6). The maximum surface rut at 'failure' (N = 44,690) is between 50.8 to 68.6 mm (2 to 2.7 inches) and compared to LFC1 and LFC2 sections, the surface upheaval is smaller.

Medium-Strength Sections

The TSPs measured along profile lines 1 and 2 are plotted in Figure 7 and Figure 8 for the medium-strength flexible test sections (MFC and MFS). In the case of MFC1 and MFC2, the maximum surface rut at the termination of test trafficking (N = 12,952) is between 76.2 to 101.6 mm (3 to 4 inches) in both the traffic wheel paths (see Figure 7). The surface upheaval varies between 30.5 to 50.8 mm (1.2 to 2 inches). In the B 777 wheel path, the maximum surface rut at 'failure' is about 89 mm (3.5 inches) for MFS1 and 38.1 mm (1.5 inches) for MFS2, while it is about 25.4 mm (1 inch) in B 747 wheel paths for both MFS1 and MFS2 (see Figure 8).

Rut Depth (RD) Measurements Using a Straightedge

The rut depths were measured with a 3.6-m (12-foot) long straightedge at the same longitudinal stations and at approximately the same times during trafficking as the TSPs. The maximum deviation of the pavement surface from the straightedge (with the straightedge placed transverse to and centered in the traffic wheel path) was recorded as the measured rut depth. As the traffic wheel path was approximately the same width as the length of the straightedge, the straightedge measurements did not include any indication of permanent deformation outside the wheel path. Some rutting had previously accumulated during the slow-rolling response testing. The rut depth at the start of the traffic testing was subtracted from the traffic test rut depth measurements; thus, the reported results show the accumulation of rutting due to traffic.

Comparison of TSP and Straightedge Rut Depths

As N increases, the TSP-based rut depth measurements exceed the straightedge rut depths. This is because, as the rut width increases above 305 mm (12 feet) due to the effect of trafficking, the position of the 3.6-m (12-ft) straightedge goes down, thus recording smaller rut depths. It is also noted that the accuracy of straightedge measurements depends mostly on the ability of the operator to correctly place the straightedge to measure the maximum ruts in the profile (Gramling et al 1991).

Low-Strength Sections

The straightedge rut depth measurements are compared against the TSP-based maximum rut depths in Figure 9 and Figure 10 for LFC and LFS test sections respectively. The arrow in the Figures indicates where after 20,000 load repetitions the trafficking load magnitude, in the case of LFC and LFS test sections, was increased from 20.4 tonnes (45,000 lbs) to 29.4 tonnes (65,000 lbs). The rutting observed under 20.4 tonnes (45-Kips) loading is stable and uniform for both LFC and LFS sections. Under the 29.4 tonnes (65-Kips) loading, rutting increases rapidly as the test sections approach 'failure' indicating unstable performance. An initial rutting followed by a decreasing rutting rate with subsequent load applications (N) indicates a stable pattern while unstable performance is characterized by a rapid/inconsistent increase in rutting with increasing number of load repetitions (Bejarano and Thompson 1999). A higher rate of rutting is observed in LFC compared to LFS.

Medium-Strength Sections

Comparisons of straightedge rut depth measurements versus TSP-based rut depth measurements are shown in Figure 11 and Figure 12 for MFC and MFS test sections respectively. The maximum MFC surface rut at failure (N = 12,952) is almost twice that of MFS (N = 19,869). For all of MFS TSPs, except B777-MFS1, the rate of rutting approaches zero at 'failure' (N = 19,869). However, the B777 traffic lane in MFS1, exhibited a rapid increase in surface rutting after 12,000 load repetitions. The reason for this aberrant behavior is not yet known. The NAPTF staff has indicated that a portion of the pavement on the North side (B 777) of the MFS section can be considered a separate case due to construction related problems.

In the medium-strength sections, a stable rutting trend is seen until about 10,000 passes. However, as the test sections approach 'failure', rutting increases rapidly and abruptly, indicative of unstable performance.

Differences in Max. Rut Depths between B777 Trafficking and B747 Trafficking

In each flexible test section, in addition to profile lines 1 and 2, TSPs were also measured at additional longitudinal stations such as at the beginning of a test section, approximate center of the test section and at the end of the test section. The location of additional profile lines along with the main profile lines (1 and 2) are shown in Figure 14 for medium-strength test sections and in Figure 13 for low-strength test sections. For a given number of load repetitions (N), each profile line contributes to a pair of maximum rut depths (RDs) at the same test conditions: one for B777 trafficking and one for B747 trafficking. The differences in maximum rut depths between B777 trafficking and B747 trafficking at each profile line are plotted in Figure 16 for medium-strength test sections and in Figure 15 for low-strength test sections.

Low-Strength Sections

In the case of low-strength test sections (see Figure 15), the absolute differences in maximum rut depths between B777 trafficking and B747 trafficking do not exceed 10.2 mm (400 mils) for any of the profile lines. The scatter and the absolute magnitude of the differences increase abruptly when the wheel loads increase from 20.4 tonnes (45,000 lbs) to 29.4 tonnes (65,000 lbs) after 20,000 load repetitions. The differences are more or less scattered around a mean value of zero indicating that the B777 and B747 rut depths are similar in the low-strength test sections.

Medium-Strength Sections

In Figure 16, it is seen that for MFC test sections, the maximum rut depth differences do not exceed an absolute value of 12.7 mm (500 mils) for any of the profile lines until about 10,000 load repetitions. During the last 3,000 load repetitions, the differences increase rapidly approaching an absolute value of 38.1 mm (1500 mils). The B747 rut depths are consistently higher than the B777 rut depths. In the MFS test section, the B777 rut depths are consistently higher than B747 rut depths and the differences increase as trafficking progresses; approaching an absolute difference of 25.4 mm (1000 mils). As noted earlier, the B777 trafficking side is considered as a separate case due to construction related problems. Therefore, any conclusion drawn regarding the differences in maximum rut depths in MFS test section must be treated with caution.

Paired t-Tests

To establish if the rut depths obtained under B777 trafficking are *significantly* different (higher or lower) from those under B747 trafficking, paired t-tests were performed. The straightedge rut depths were considered unreliable and therefore not used in this study. For a given number of load repetitions (N), each profile line contributes to a pair of maximum rut depths (RDs) and therefore *one* value for difference in the rut depths. It is noted from Figure 13 and Figure 14 that each test section has 3 to 4 profile lines and thus 3 or 4 samples (n). The tests were performed at specific number of load repetitions such as at N = 2000, 4000, etc. until the number of repetitions to reach 'failure'. It is noted that the paired t-tests were conducted on the low-strength sections only for the 29.4 tonnes (65-Kips) wheel load rutting data as the differences in rut depths under 20.4 tonnes (45,000 lbs) wheel loading were very minimal as noted earlier. The significance level (α) was set to 0.05 for all the tests. The results of paired t-tests are shown in Figure 17 for low-strength test sections and in Figure 18 for medium-strength test sections. In the Figures, the symbol 'R' means that the results are statistically significant; thus rejecting the null hypothesis, i.e., the mean B777 rut depths (μ_{B777}) are *significantly* different (higher or lower) than the mean B747 rut depths (μ_{B747}) at a given number of load repetitions (N).

Low-Strength Sections

For LFC (Figure 17 - Top), there is not enough evidence to conclude that the mean B777 rut depths are significantly higher or lower than the mean B747 rut depths. The same is true for LFS test section (Figure 17 - Bottom) except towards the end of traffic testing where the mean B747 rut depths are found to be *significantly* higher than the mean B777 rut depths at the 0.05 significance level. However, the actual magnitude of differences does not exceed a maximum value of 5.1 mm (200 mils) which is considered insignificant from an engineering standpoint.

Medium-Strength Sections

For the MFC test section (Figure 18 - Top), the mean B777 rut depths are similar to mean B747 rut depths except towards the end of traffic testing (N = 7000, 9000 and 10000) where the results are statistically significant at the 0.05 significance level. Though, the mean B747 rut depths are consistently and *significantly* higher than the mean B777 rut depths for these three cases, the maximum absolute difference is only 10.2 mm (400 mils). In the case of the MFS test section (Figure 18 - Bottom), the results are statistically significant for all the cases, i.e., the mean B777 rut depths are significantly higher than the mean B747 rut depths throughout trafficking. The maximum absolute difference is around 17.8 mm (700 mils).

Number of Load Repetitions to Reach Specific Rut Depth Levels

The number of load repetitions (N) to reach specific rut depth levels (as per standard "pavement distress criteria") is recorded in Table 2 for low-strength test sections and in Table 3 for medium-strength test sections. These rut depth levels are typically used by most airport agencies to trigger maintenance and rehabilitation activities. At the 25.4-mm (1-inch) rut depth level, which is one of the popular failure criteria (US COE 2001), the number of passes required by the B777 and that required by the B747 are similar. This is more apparent in low-strength test sections than in medium-strength test sections. The difference is, however, significant in MFS1 which confirms what has been previously said about the MFS test section.

Rutting Models

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. The NCHRP 1-26 (1990) study considered several material permanent strain accumulation models and pavement system rutting models and concluded that the predominant flexible pavement rutting model is the log permanent strain-log load repetitions phenomenological model, also known as the power model. The power model is expressed as follows:

$$\log \varepsilon_p = a + b \log N$$

or

$$\varepsilon_p = AN^b \tag{1}$$

where
ε_p = permanent strain,
a and b = experimentally determined factors, and
A = antilog of a.

Thompson and Nauman (1993) noted that the model was applicable to all conventional flexible paving materials (asphalt concrete and granular materials) and subgrade soils. They concluded that flexible pavement surface rutting (an accumulation of permanent deformation from all of the paving layers and subgrade) can be characterized by a phenomenological model of the same form:

$$\log RD = a + b \log N$$

or

$$RD = AN^b \tag{2}$$

where
RD = rut depth (mm or mils),
a and b = experimentally determined factors, and
A = antilog of a.

The NCHRP 1-26 (1990) study indicated that for reasonable stress states (considerably below material failure strengths), the 'b' term in the model is generally in the range of 0.1 to 0.2. The 'A' term is quite variable and is strongly influenced by material/soil type, repeated stress state, and factors influencing material shear strength (Thompson and Nauman, 1993).

Another popular permanent strain accumulation prediction model is the Ohio State University (OSU) model included in a pavement design system developed for the Ohio Department of Transportation (Thompson and Nauman, 1993). The model (in terms of surface rutting) is:

$$RD / N = AN^m \tag{3}$$

where
RD = rut depth at N load repetitions (mm or mils),
N = number of repeated load applications,
A = experimental constant dependent on material and state of stress conditions, and
m = experimental constant depending on material type.

Thompson and Nauman (1993) proposed and evaluated a phenomenological pavement surface rutting rate (RR) model based on the power model (1) and the OSU model (3):

$$RR = RD/N = AN^B \tag{4}$$

where
RR = rutting rate,
RD = rut depth (mm or mils),
N = number of repeated load applications, and

A and B = terms developed from field calibration testing data

Note that in (4), B = b - 1, where b is the slope of the power model (1).

The model proposed by McLean and Monisimith (1974) for asphalt concrete was also evaluated. In terms of surface rutting, the third-order polynomial model is

$$\log RD = C_0 + C_1(\log N) + C_2(\log N)^2 + C_3(\log N)^3 \tag{5}$$

where
RD = rut depth (mm or mils)
C_0, C_1, C_2, and C_3 = regression parameters

NAPTF Rutting Analyses

Using the maximum surface ruts obtained from the TSPs, rutting analyses were performed by applying the power model and the third-order polynomial model. It is noted a priori that these rutting models are best suited for modeling stable rutting performance. The B777 rut depths and the B747 rut depths were separately analyzed and compared. The rutting analyses were performed using two approaches: (1) to consider the NAPTF 'failure' criterion, i.e., to consider all of the rutting data in the analyses, and (2) to consider rutting until it reached specific levels of rut depths (ex., 25.4 mm [1 inch], 38.1 mm [1.5 inch], etc.) which are frequently used in triggering maintenance and rehabilitation activities at airports. The second approach ensures that only stable rutting trends are considered for analysis.

Power Model

Until 'Failure'

The maximum RDs were plotted against the number of load repetitions (N) until 'failure' as defined by the NAPTF failure criterion and the data were analyzed using the power model to obtain the parameters A and b. The objective was to observe the effects of loading gear configuration (B777 versus B747), profile line location (profile line 1 versus profile line 2), and presence (absence) of a stabilized base course on model parameters A and b.

In the low-strength sections, two different wheel load levels were used; 20.4 tonnes (45,000 lbs or 45-Kips) until 20,000 passes and 29.4 tonnes (65,000 lbs or 65-Kips) after 20,000 passes. Two different rutting trends were observed (see Figure 9 and Figure 10). It is expected that the model coefficients would be different for rutting under 20.4-tonnes (45-Kips) wheel loading and under 29.4-tonnes (65-Kips) wheel loading. The maximum rut depth did not reach up to 25.4 mm (1 inch) during the first 20,000 passes in the low-strength test sections when 20.4-tonnes (45-Kips) wheel load was used. In the case of LFC1 and LFC2, the maximum rut depth at the end of 20,000 passes is between 0.6 to 0.9 inch. In the case of LFS1 and LFS2, it is between 0.4 to 0.7 inch. In modeling the rutting data obtained under the 29.4-tonnes

(65-Kips) wheel loading, the pre-accumulated rutting during the first 20,000 passes was neglected (i.e., rutting at the initiation of 29.4 tonnes [65-Kips] traffic loading was set to zero).

The results of the analyses are summarized in Table 4 and Table 5 for low- and medium-strength test sections respectively. For the low-strength test sections, the rutting rates (values of b), in general, are higher under 29.4-tonnes (65-Kips) loading compared to 20.4-tonnes (45-Kips) loading. Under 20.4-tonnes (45-Kips) loading, the rutting rates are higher for medium-strength test sections compared to low-strength test sections. All of the R^2 values in Table 4 and Table 5 are significant at the 99% probability level. The Standard Error of Estimates (SEEs) are low (ranging from 35 to 115 mils) for the low-strength sections but are relatively higher (ranging from 172 to 610 mils) for the medium-strength sections.

Until Specific Rut Depth Levels

Rutting analyses were performed by considering specific levels of maximum rut depths that are frequently used in triggering maintenance and rehabilitation activities. Two specific cases were considered: (1) until the rut depth reached 25.4 mm (1 inch) and (2) until the rut depth reached 38.1 mm (1.5 inches). From the rutting data, portions of the data relevant to these two cases were used in the rutting analysis. Regression analyses were performed to obtain the model coefficients A and b.

The results of the analyses are summarized in Table 6 and Table 7 for medium-strength test sections for both the cases. It is noted for MFS1 and MFS2 that, the maximum rut depth did not exceed 27.9 mm (1.1 inches) in the B747 traffic lane. In general, the R^2 values are lower and the SEE values are higher (ranging from 3.3 mm [132 mils] to 4.4 mm [173 mils] for case 1 and 4.4 mm [172 mils] to 5.5 mm [218 mils] for case 2) for MFS test sections compared to MFC test sections (ranging from 0.9 mm [37 mils] to 1.1 mm [43 mils] for case 1 and 1.1 mm [42 mils] to 2.3 mm [92 mils] for case 2). The R^2 values are lower and the SEE values are higher for case 2 than for case 1, for both the test sections. This approach was not used to analyze low-strength section rutting data.

The model parameters obtained using this approach are compared with those obtained using the previous approach in Figure 19 for medium-strength test sections.

Third-Order Polynomial Model

Until 'Failure'

The results of linear regression analyses using the third-order polynomial model are shown in Table 5 and Table 6 for low and medium strength flexible test sections respectively. As seen in the Tables, a very good fit accompanied by lower SEEs (ranging from 0.6 mm [24 mils] to 2.0 mm [78 mils] for low-strength sections and 1.6 mm [62 mils] to 6.0 mm [235 mils] for medium-strength sections) were found for all rutting data using the third-order polynomial rutting model.

Comparison of Power Model and Third-Order Polynomial Model

All of the R^2 values obtained using the power model were significant at the 99% probability level. In comparison to the power model, higher R^2 values and lower SEE values were obtained using the third-order polynomial rutting model. However, the third-order polynomial model parameters (C_0, C_1, C_2, and C_3) do not show consistent behavior, but vary considrably (see Table 8 and Table 9). For instance, in LFC2, the C_1, C_2, and C_3 parameters are sometimes positive and sometimes negative and vary in terms of magnitude (see Figure 20). Thus, the third-order polynomial model is a good curve-fitting model in terms of producing higher R^2 and lower SEE values, but its engineering significance is questionable. On the other hand, the parameters (A and b) of the power model are consistent (see Table 4 to Table 7), and meaningful (i.e. parameter A is proportional to the magnitude of rutting and parameter b is the rutting rate), and therefore comparable.

Pavement Surface Rutting Rate Model

Thompson and Nauman (1993) evaluated and validated the pavement surface rutting rate (RR) model (4) by analyzing selected AASHO Road Test data and rutting performance information from Illinois Department of Transportation rehabilitated sections of the AASHO Road Test flexible pavement tangent sections. The Road Test data showed that stable pavement rutting trends were related to estimated pavement structural responses, particularly the subgrade stress ratio (SSR). They concluded that the RR model is particularly helpful in analyzing rutting data for a specific pavement section and estimating the future rutting for pavement management system activities.

The rutting rates are plotted against the number of load repetitions (N) on a Log-Log scale for LFC and LFS test sections in Figure 21 and Figure 22 respectively. The same information is plotted for medium-strength sections in Figure 23. The Figures show a linear relation between rutting rate and N for both low- and medium-strength sections, under 20.4-tonnes (45-Kips) wheel loading. As the low-strength test sections (under 29.4-tonnes [65-Kips] wheel loading) and medium-strength test sections (under 20.4-tonnes [45-Kips] wheel loading) approach 'failure', the rutting rates increase with increasing number of load repetitions, indicative of unstable rutting performance.

Summary

The National Airport Pavement Test Facility (NAPTF) was constructed to generate full-scale testing data to support the investigation of the performance of airport pavements subjected to complex gear loading configurations of new generation aircraft (NGA). Two gear configurations, a six-wheel tridem landing gear (B777) in one lane and a four-wheel dual-tandem landing gear (B747) in the other lane were tested simultaneously. To monitor rutting, transverse surface profile (TSP) measurements and rut depth measurements using a 3.6-m (12-ft.) straightedge were made throughout the traffic test program. Except for the high-strength flexible test sections (HFC and HFS) which are not considered in this paper, trafficking continued until the individual pavement test sections were considered as 'failed'. The NAPTF 'failure' criterion is defined as the presence of at least 25.4 mm (1 inch) surface upheaval adjacent to the traffic lane. The significant findings of the rutting study are

- In general, the maximum rut depth at 'failure' is higher for conventional-base flexible test items than for stabilized-base flexible test items. More passes at higher wheel loads was required by low-strength test sections to reach 'failure' compared to medium-strength test sections. It is noted that the total pavement thicknesses (excluding the subgrade) are 1245 mm (49 in.) and 1003 mm (39.5 in.) for LFC and LFS test sections respectively, while they are 635 mm (25 in.) and 457 mm (18 in.) for MFC and MFS test sections respectively.

- The number of passes required by B777 and B747 gears in order to reach a 25.4-mm (1-inch) rut depth was similar.

- Results of the paired t-tests (of the mean rut depths) between the B777 trafficking and the B747 trafficking showed that the rut depths do not differ significantly between the two test gears.

- The power model, used in the rutting analysis, was statistically significant at the 99% probability level for all of the sections.

- The third-order polynomial model was "better than" the power model in terms of producing higher R^2 values and lower SEE values. However, the "engineering significance" of the model parameters is questionable.

- There is a linear relation between rutting rate (RR) and N for both low- and medium-strength sections, under 20.4-tonnes (45-Kips) wheel loading.

- The pavement surface rutting rate model captures the unstable rutting trend (increasing rutting rate with increasing N) as the test sections approach 'failure'.

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The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Aviation Administration. This paper does not constitute a standard, specification, or regulation.

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Table 1. Number of Passes to 'Failure' for NAPTF Test Sections

NAPTF Test Section	Number of Passes to 'Failure'		
	Wheel Load = 20.4 tonnes (45-Kips)	Wheel Load = 29.4 tonnes (65-Kips)	Total
MFC	12952*	0	12,952
MFS	19869*	0	19,869
LFC	19950	24145	44095*
LFS	19939	24749	44688*

* - 'Failure' achieved.

Table 2. Number of Load Repetitions to Reach Specific Rut Depth Levels in Low-Strength Test Sections (1 mil = 0.0254 mm)

Rut Depth (mils)	LFC1		LFC2		LFS1		LFS2	
	B-777	*B-747*	*B-777*	*B-747*	*B-777*	*B-747*	*B-777*	*B-747*
250	28	516	28	531	10,743	12,442	28	28
500	5,008	8,083	7,791	8,723	20,068	20,642	15,111	515
750	20,076	16,291	16,291	20,406	21,152	22,888	20,642	20,228
1000	**21,612**	**21,414**	**21,084**	**22,759**	**22,888**	**26,153**	**21,488**	**21,488**
1500	27,440	25,871	24,383	28,115	36,765	38,283	26,618	26,618

Table 3. Number of Load Repetitions to Reach Specific Rut Depth Levels in Medium-Strength Test Sections (1 mil = 0.0254 mm)

Rut Depth (mils)	MFC1		MFC2		MFS1		MFS2	
	B-777	*B-747*	*B-777*	*B-747*	*B-777*	*B-747*	*B-777*	*B-747*
250	28	28	28	28	28	28	28	5,295
500	299	133	133	133	3,346	10,529	5,373	7,513
750	1,193	363	363	363	5,295	13,213	9,883	11,877
1000	**3,343**	**1,193**	**1,193**	**1,448**	**6,539**	**19,869**	**12,440**	**15,108**
1500	6,533	4,695	5,294	5,300	11,353	-	16,290	-

Table 4. Summary of Power Model Parameters for Low-Strength Sections (until 'Failure') (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

Until 'Failure'							
			LFC1				
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	A	b	b - 1	R^2	SEE (mils)
B777	45	44,095	96.86	0.19	-0.81	0.85	57
B747			52.29	0.26	-0.74	0.88	73
B777	65		1.19	0.73	-0.27	0.98	45
B747			0.83	0.77	-0.23	0.99	35
			LFC2				
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	A	b	b - 1	R^2	SEE (mils)
B777	45	42,885	98.54	0.19	-0.81	0.72	91
B747			60.78	0.23	-0.77	0.89	54
B777	65		1.18	0.74	-0.26	0.96	57
B747			0.17	0.93	-0.07	0.98	51
			LFS1				
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	A	b	b - 1	R^2	SEE (mils)
B777	45	44,688	19.65	0.27	-0.73	0.66	72
B747			7.34	0.35	-0.65	0.74	55
B777	65		5.93	0.55	-0.45	0.94	101
B747			3.49	0.59	-0.41	0.95	115
			LFS2				
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	A	b	b - 1	R^2	SEE (mils)
B777	45	44,690	165.93	0.09	-0.91	0.36	77
B747			197.88	0.11	-0.89	0.60	69
B777	65		3.87	0.59	-0.41	0.95	86
B747			2.34	0.66	-0.34	0.97	89

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Table 5. Summary of Power Model Parameters for Medium Strength Sections (until 'Failure') (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

Until 'Failure'							
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFC1				
			A	b	b - 1	R^2	SEE (mils)
B777	45	12,952	54.63	0.38	-0.62	0.75	450
B747			65.46	0.38	-0.62	0.89	275
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFC2				
			A	b	b - 1	R^2	SEE (mils)
B777	45	12,952	106.34	0.32	-0.68	0.82	316
B747			60.91	0.40	-0.60	0.76	611
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFS1				
			A	b	b - 1	R^2	SEE (mils)
B777	45	19,869	20.74	0.46	-0.54	0.79	585
B747			32.08	0.31	-0.69	0.70	173
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFS2				
			A	b	b - 1	R^2	SEE (mils)
B777	45	19,869	12.90	0.45	-0.55	0.86	242
B747			6.93	0.48	-0.52	0.88	182

Table 6. Summary of Power Model Parameters for Medium-Strength Sections (until Rut Depth = 1 inch) (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

Rut Depth = 1 inch							
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1-in. Rut Depth	MFC1				
			A	b	b - 1	R^2	SEE (mils)
B777	45	3,343	128.83	0.25	-0.75	0.96	43
B747		1,193	79.28	0.37	-0.63	0.98	38
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1-in. Rut Depth	MFC2				
			A	b	b - 1	R^2	SEE (mils)
B777	45	1,448	177.10	0.24	-0.76	0.97	37
B747		1,193	117.95	0.31	-0.69	0.97	39
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1-in. Rut Depth	MFS1				
			A	b	b - 1	R^2	SEE (mils)
B777	45	6,539	126.09	0.19	-0.81	0.60	132
B747		19,869	32.08	0.31	-0.69	0.70	173
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1-in. Rut Depth	MFS2				
			A	b	b - 1	R^2	SEE (mils)
B777	45	12,440	28.12	0.34	-0.66	0.76	152
B747		15,108	11.13	0.41	-0.59	0.79	163

Table 7. Summary of Power Model Parameters for Medium-Strength Sections (until Rut Depth = 1.5 inches) (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm

Rut Depth = 1.5 inches							
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1.5-in. Rut Depth	MFC1				
			A	b	b - 1	R^2	SEE (mils)
B777	45	6,533	107.25	0.28	-0.72	0.92	92
B747		4,695	99.10	0.32	-0.68	0.98	50
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1.5-in. Rut Depth	MFC2				
			A	b	b - 1	R^2	SEE (mils)
B777	45	5,294	185.08	0.23	-0.77	0.98	45
B747		5,300	137.35	0.27	-0.73	0.98	42
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1.5-in. Rut Depth	MFS1				
			A	b	b - 1	R^2	SEE (mils)
B777	45	11,353	66.50	0.29	-0.71	0.77	194
B747		19,869	32.08	0.31	-0.69	0.70	172
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 1.5-in. Rut Depth	MFS2				
			A	b	b - 1	R^2	SEE (mils)
B777	45	16,290	18.19	0.40	-0.60	0.79	218
B747		15,108	6.93	0.48	-0.52	0.88	182

Table 8. Summary of Third-Order Polynomial Model Parameters for Low-Strength Sections (Until 'Failure') (1 Kip = 0.45 tonnes; 1 mil = 0.0254 m

Until 'Failure'								
			LFC1					
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	44,095	2.389	0.133	-0.094	0.021	0.95	29
B747			1.953	0.529	-0.245	0.041	0.98	24
B777	65		-5.286	5.454	-1.363	0.129	0.98	42
B747			-2.452	2.572	-0.446	0.036	0.99	28
			LFC2					
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	44,095	2.068	0.754	-0.381	0.058	0.96	31
B747			2.515	-0.137	-0.002	0.012	0.97	24
B777	65		11.687	-10.289	3.433	-0.351	0.98	42
B747			18.842	-17.483	5.663	-0.571	0.98	39
			LFS1					
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	44,688	1.993	0.548	-0.396	0.070	0.89	37
B747			4.833	-2.941	0.810	-0.058	0.90	30
B777	65		-3.280	4.397	-1.141	0.108	0.96	78
B747			-2.376	3.602	-0.973	0.101	0.98	67
			LFS2					
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	44,690	0.518	2.574	-1.017	0.126	0.91	28
B747			1.404	1.528	-0.608	0.077	0.96	20
B777	65		-4.737	5.444	-1.419	0.135	0.97	69
B747			-5.734	6.124	-1.598	0.153	0.98	62

Table 9. Summary of Third-Order Polynomial Model Parameters for Medium-Strength Sections (Until 'Failure') (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

Until 'Failure'								
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFC1					
			C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	12,952	-0.077	3.114	-1.165	0.150	0.93	224
B747			0.107	2.680	-0.913	0.112	0.98	111
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFC2					
			C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	12,952	0.773	2.200	-0.800	0.103	0.95	160
B747			-0.896	4.155	-1.535	0.192	0.96	235
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFS1					
			C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	19,869	0.184	3.028	-1.252	0.170	0.97	169
B747			-1.987	5.210	-1.963	0.238	0.95	62
Test Gear Configuration	Wheel Load (Kips)	Number of Passes to Reach 'Failure'	MFS2					
			C_0	C_1	C_2	C_3	R^2	SEE (mils)
B777	45	19,869	4.398	-1.937	0.447	-0.014	0.98	69
B747			2.727	-0.280	-0.126	0.050	0.96	74

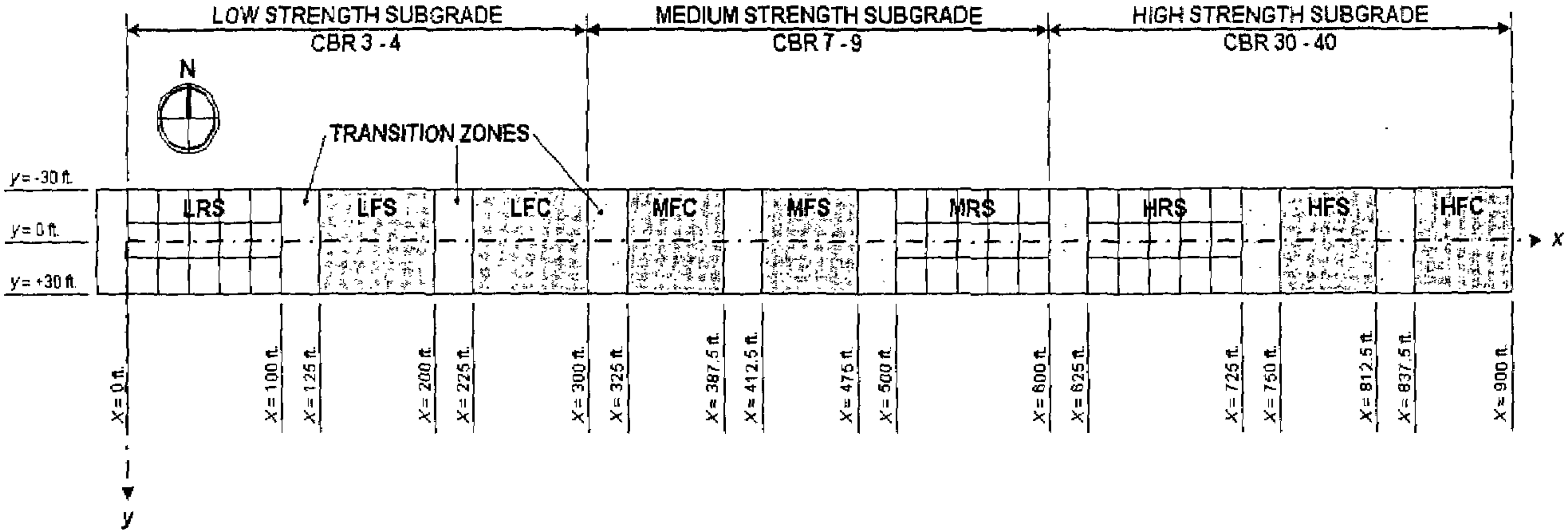


Figure 1. Plan View of NAPTF Test Sections (*Source*: http://www.airporttech.tc.faa.gov/NAPTF/TestItemPlan.asp) (1 ft. = 0.305 m)

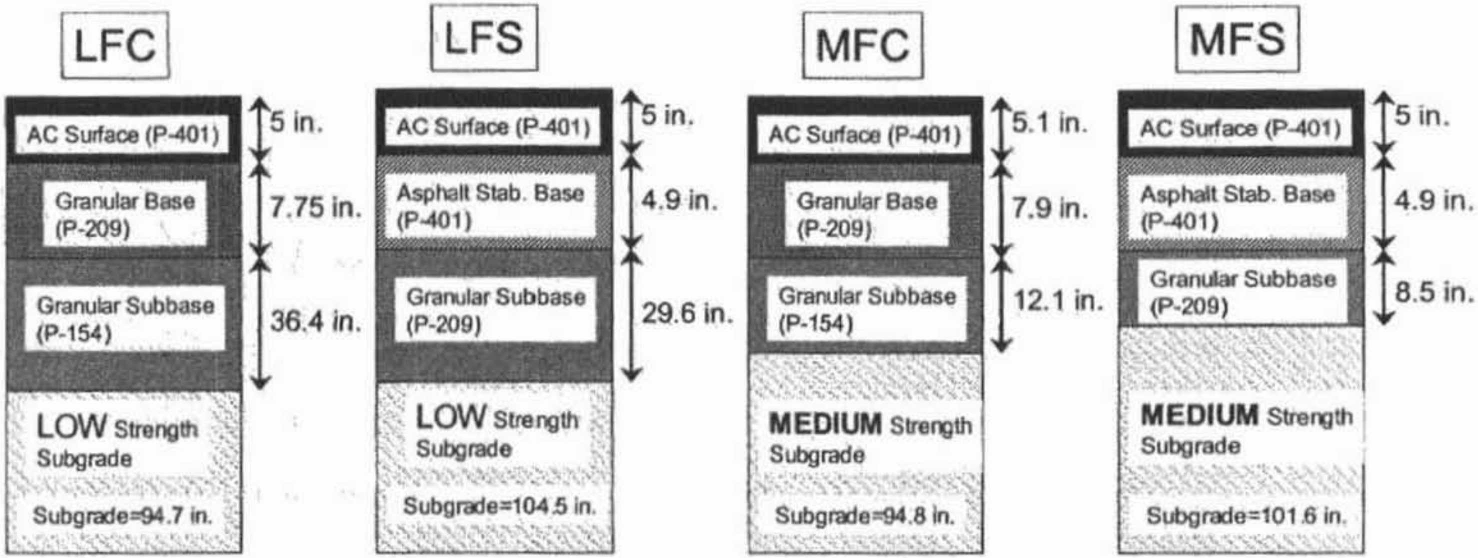


Figure 2. Cross-sectional Views of "As-Built" NAPTF Test Sections (not to scale) (1 in. = 25.4 mm)

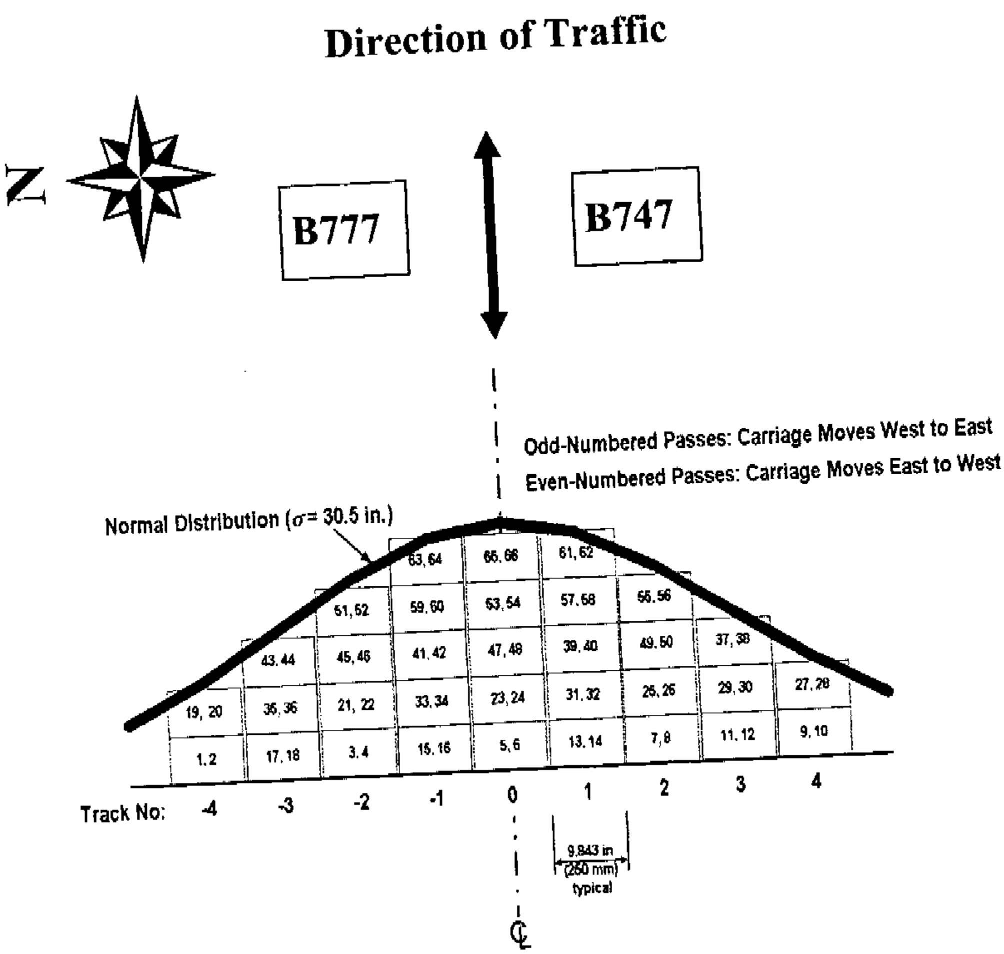


Figure 3. Wander Pattern Used in NAPTF Traffic Testing (*Source:* http://www.airporttech.tc.faa.gov/NAPTF/Wander.asp) (1 in. = 25.4 mm)

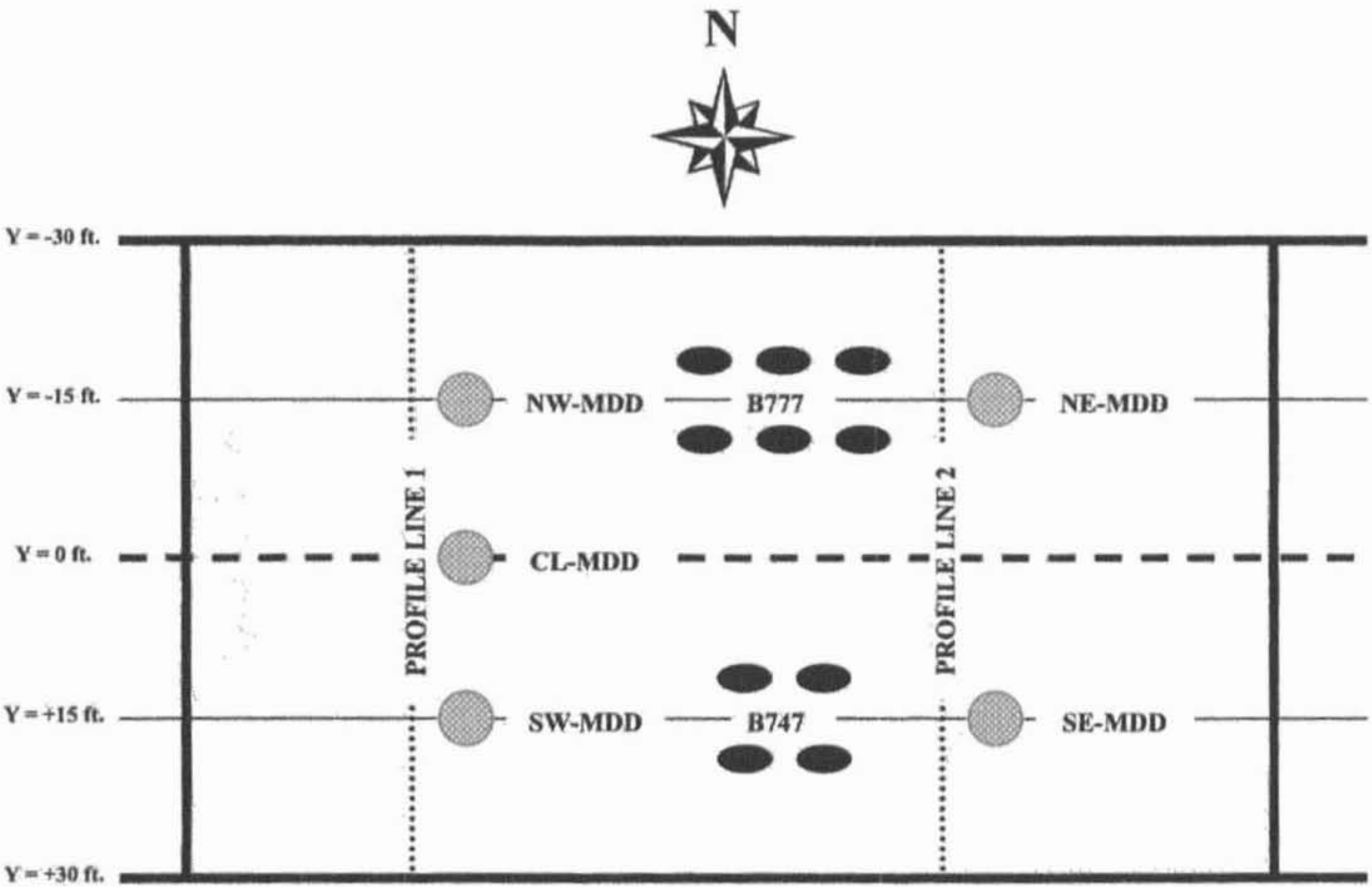
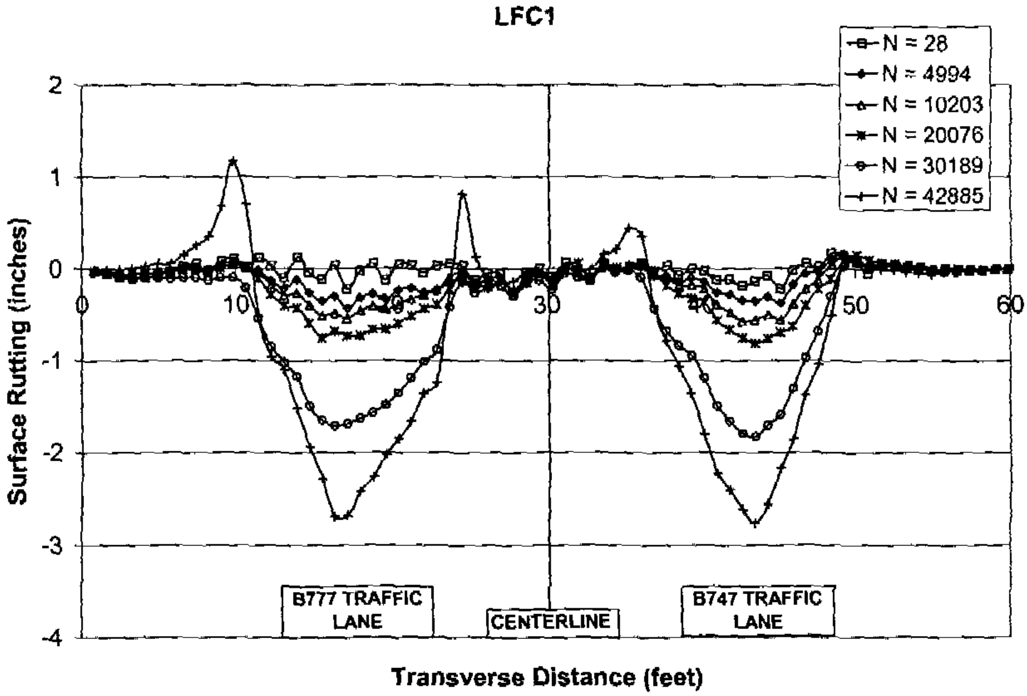


Figure 4. Location of Main Profile Lines in NAPTF Flexible Test Items with Respect to MDD Instrumentation (1 ft. = 0.305 m)



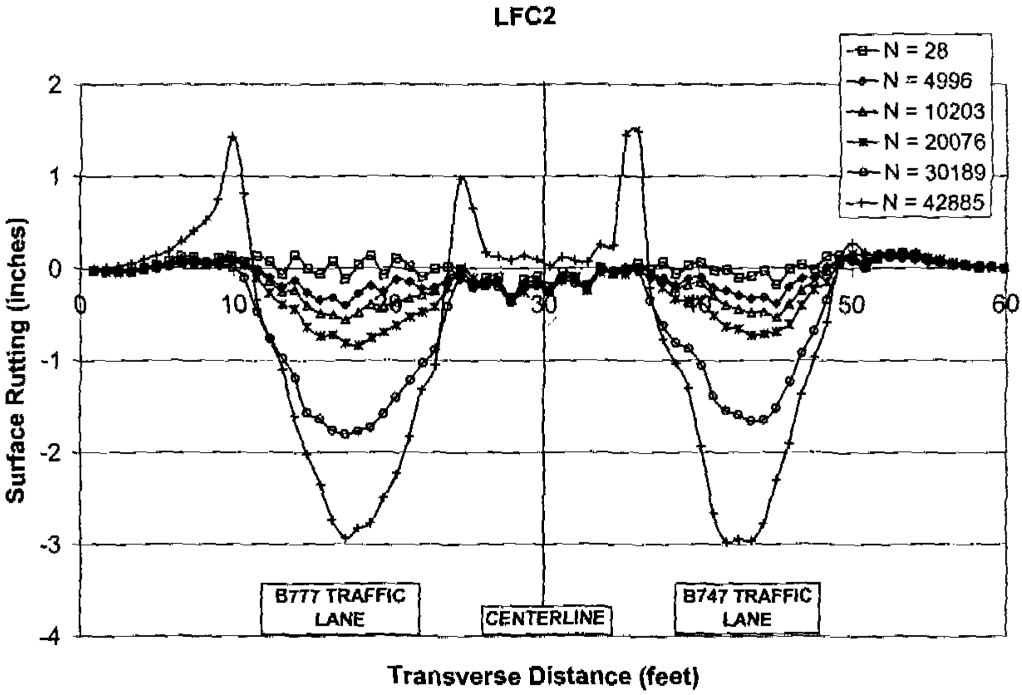
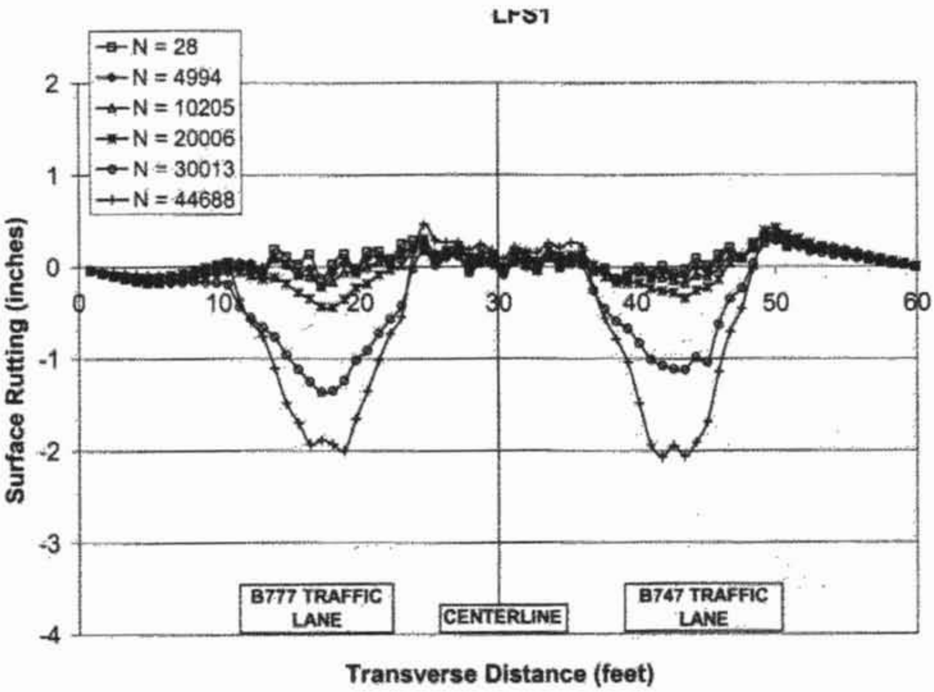


Figure 5. Transverse Surface Profiles (along Profile Lines 1 and 2) at Specific Number of Load Repetitions for NAPTF LFC Test Section (1 ft. = 0.305 m; 1 in. = 25.4 mm)



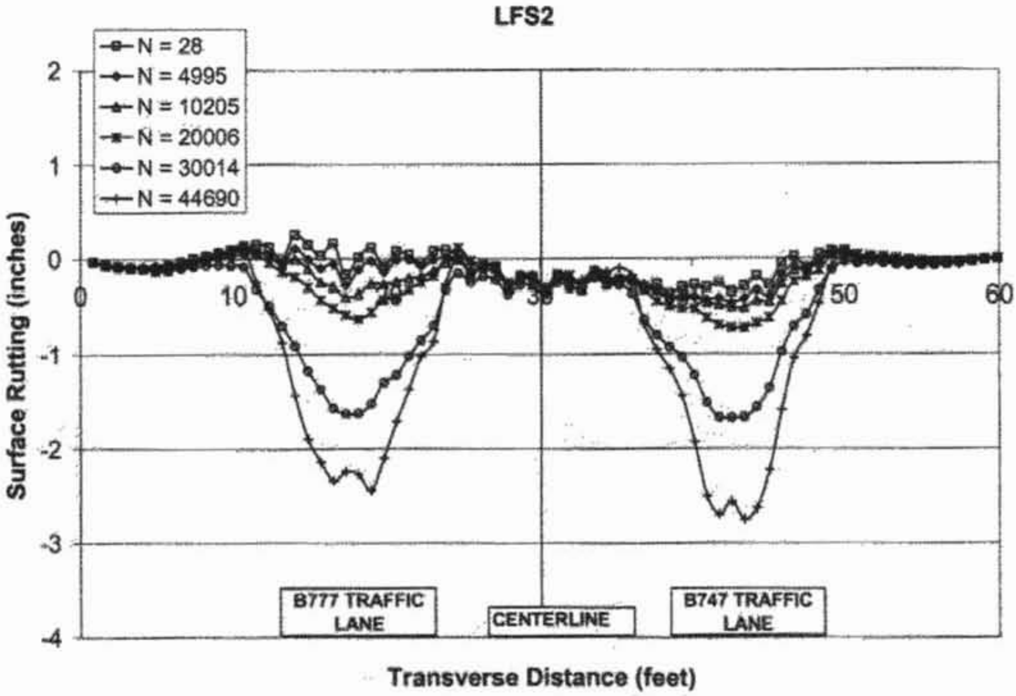
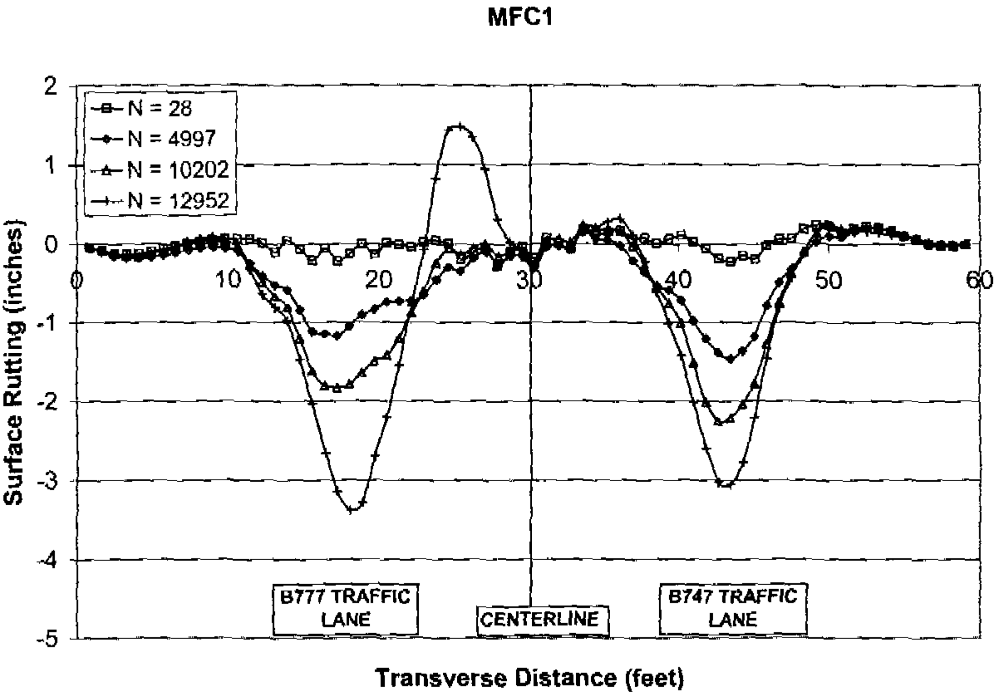


Figure 6. Transverse Surface Profiles (along Profile Lines 1 and 2) at Specific Number of Load Repetitions for NAPTF LFS Test Section (1 ft. = 0.305 m; 1 in. = 25.4 mm)



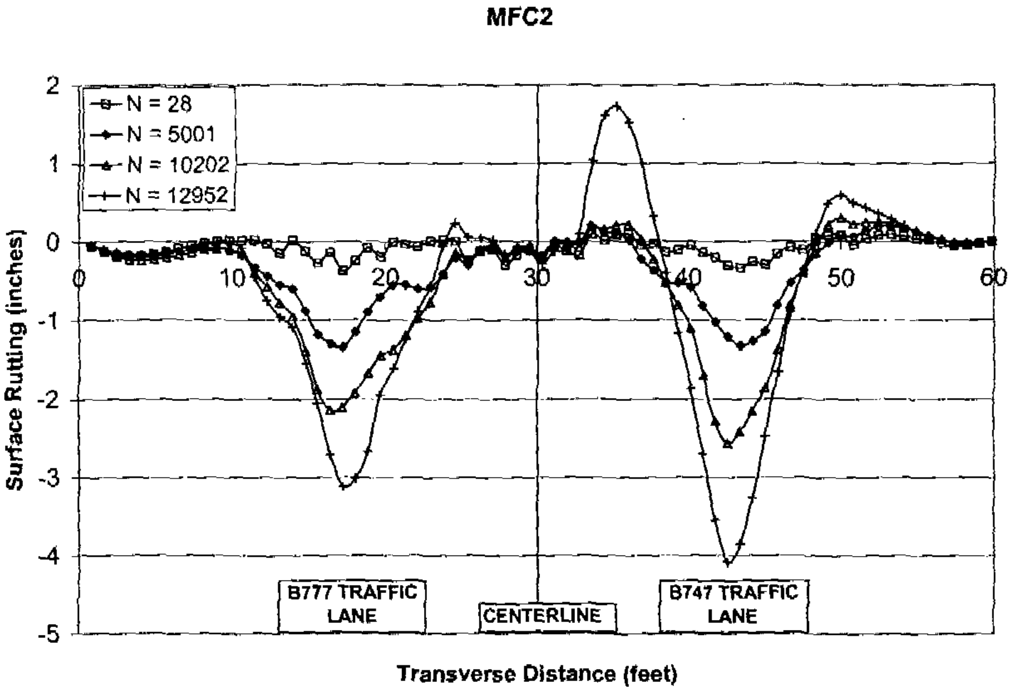
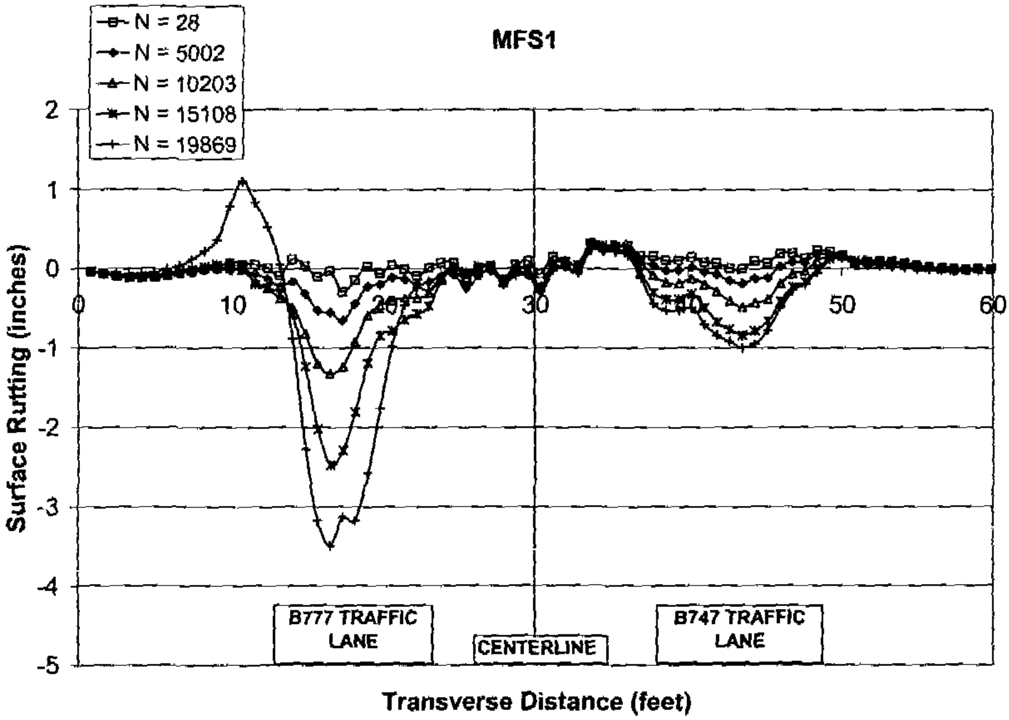


Figure 7. Transverse Surface Profiles (along Profile Lines 1 and 2) at Specific Number of Load Repetitions for NAPTF MFC Test Section (1 ft. = 0.305 m; 1 in. = 25.4 mm)



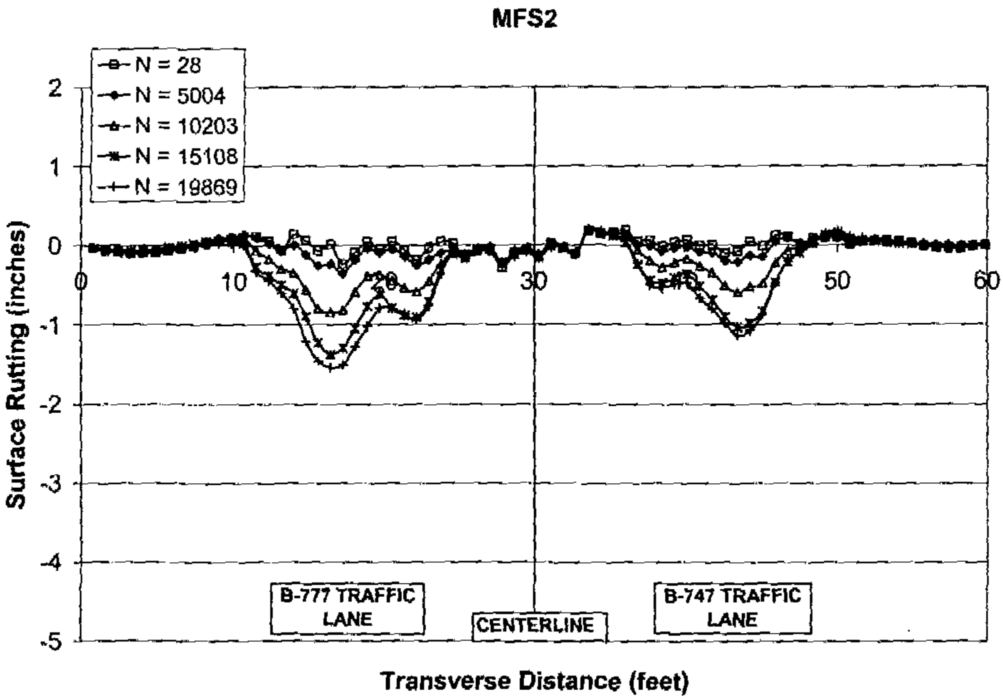
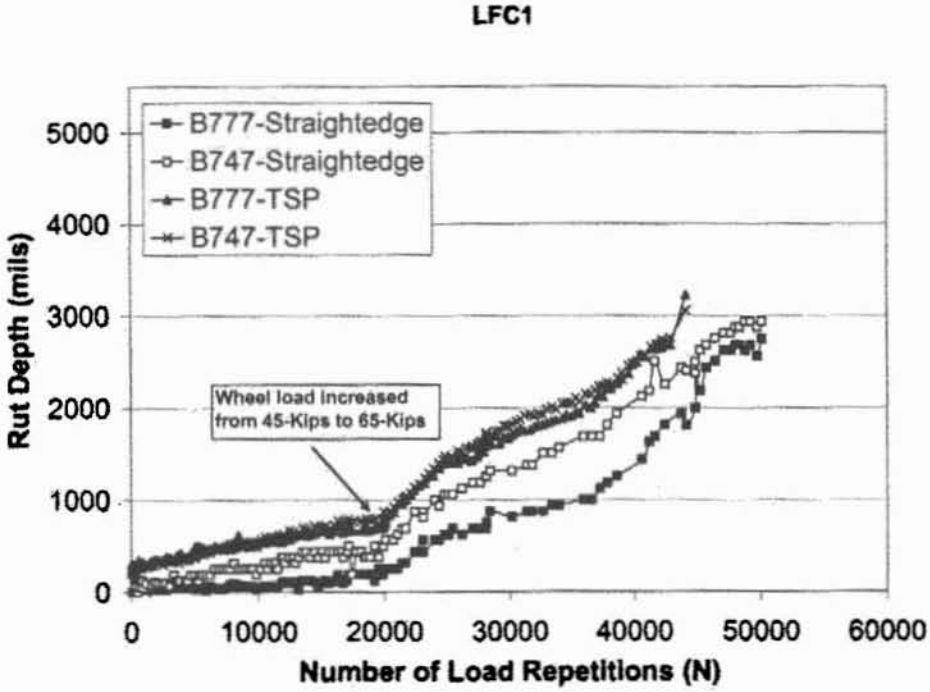


Figure 8. Transverse Surface Profiles (along Profile Lines 1 and 2) at Specific Number of Load Repetitions for NAPTF MFS Test Section (1 ft. = 0.305 m; 1 in. = 25.4 mm)



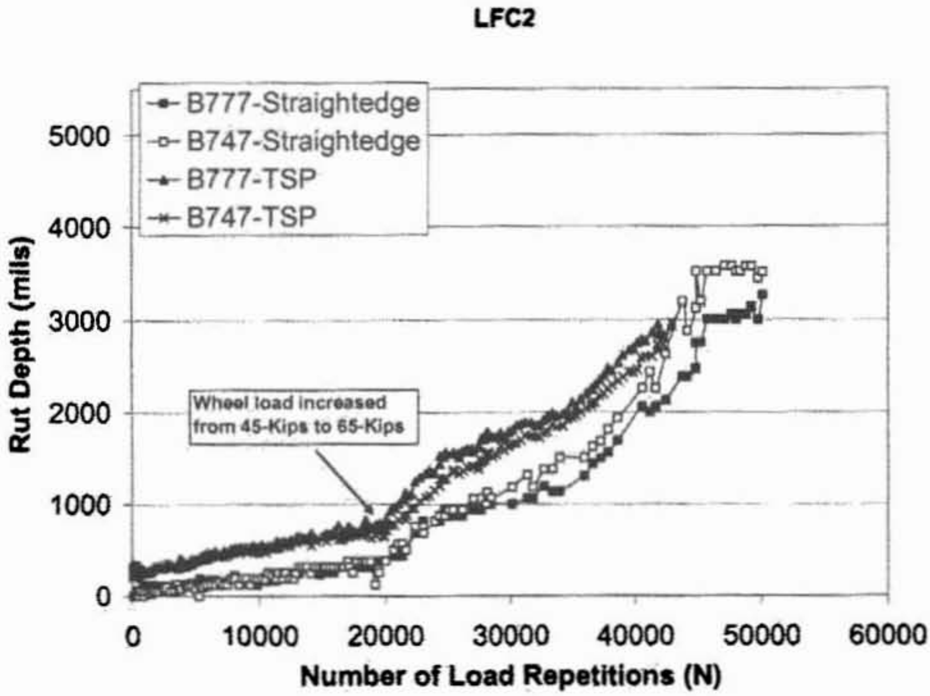
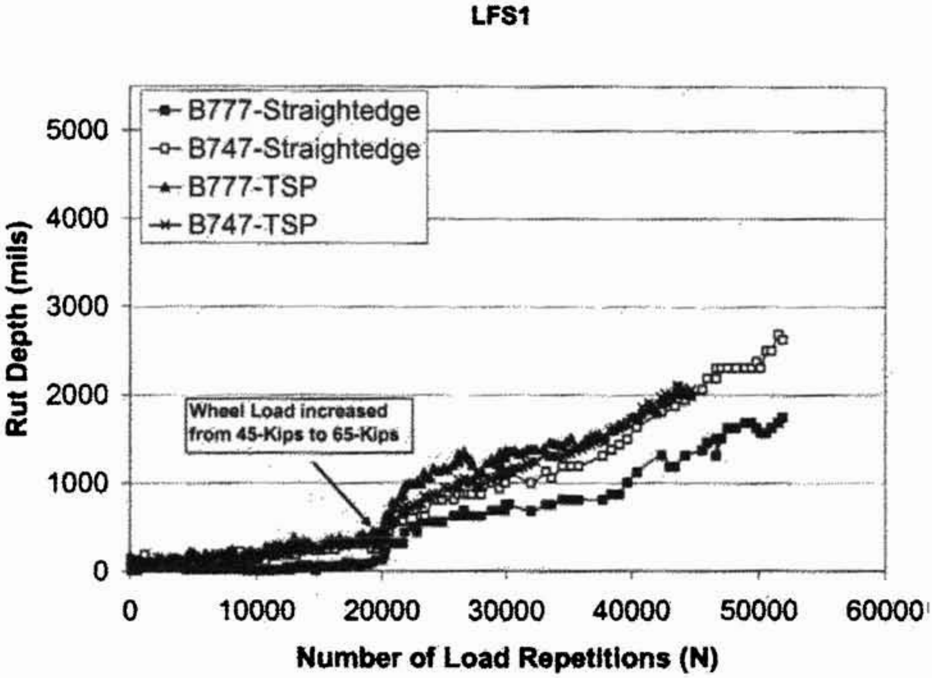


Figure 9. Comparison of Straightedge and TSP Rut Depths for LFC Test Section
(1 mil = 0.0254 mm)



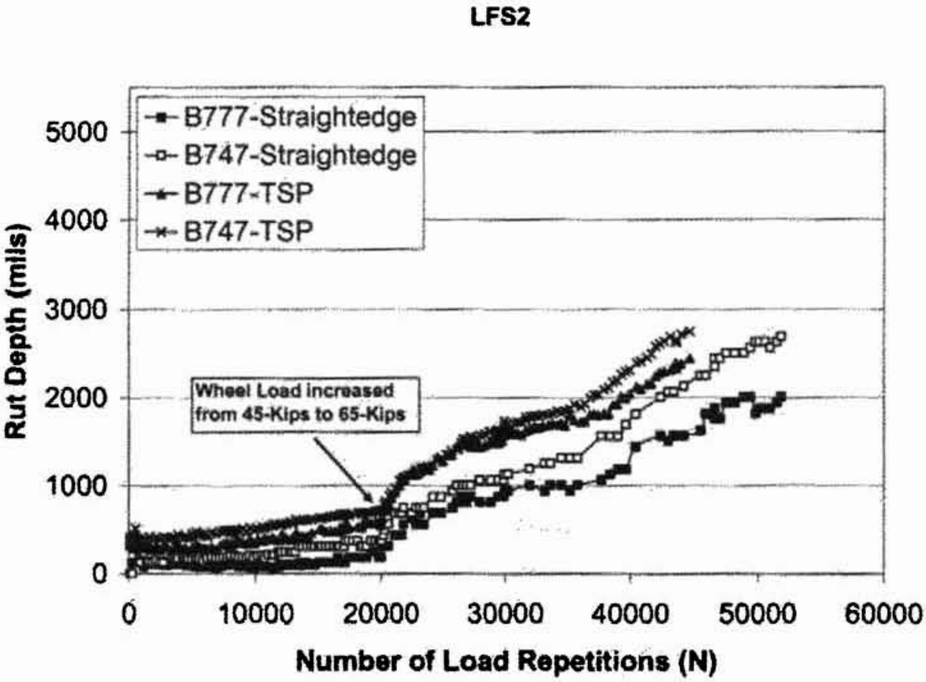


Figure 10. Comparison of Straightedge and TSP Rut Depths for LFS Test Section (1 mil = 0.0254 mm)

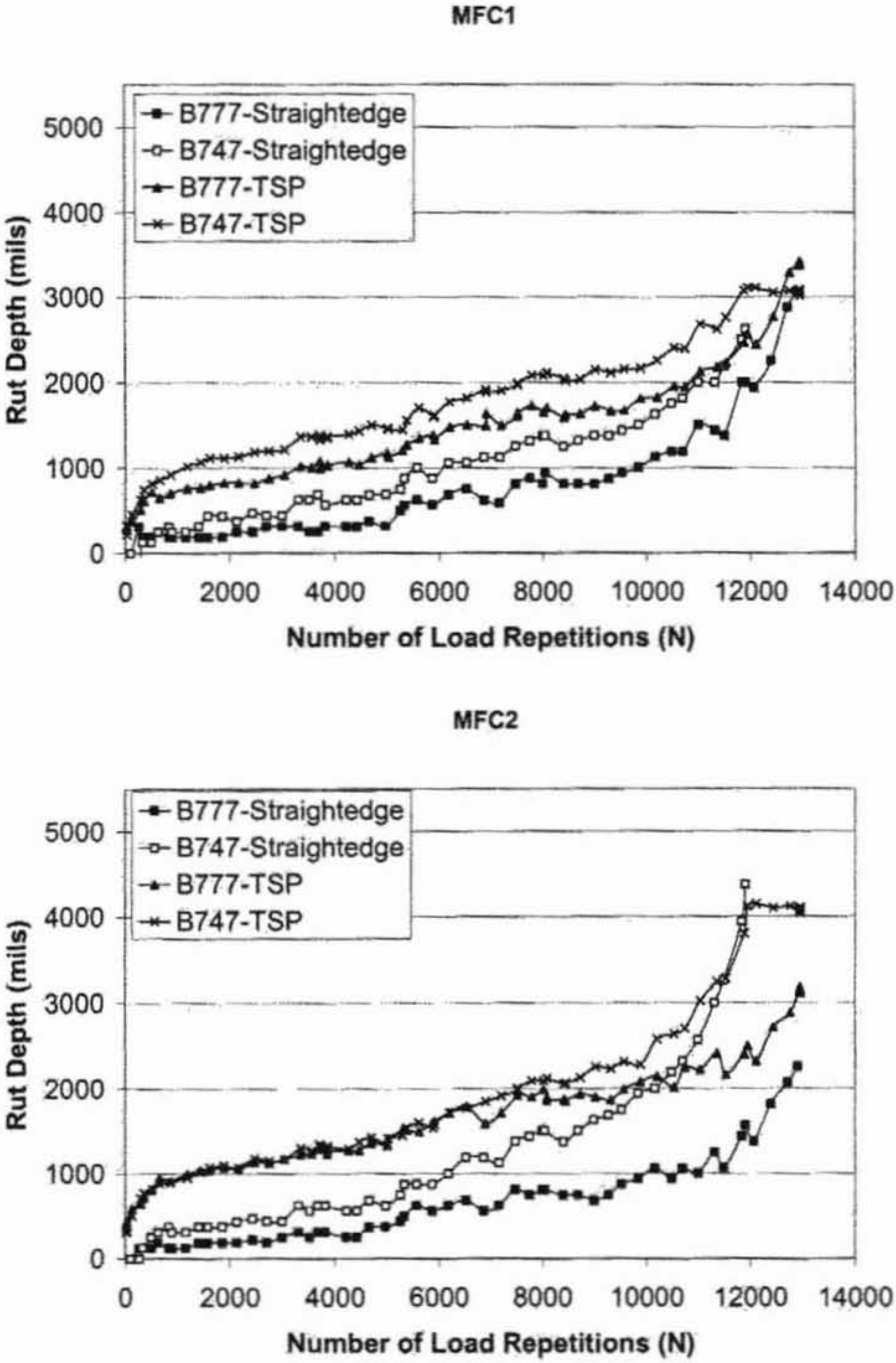
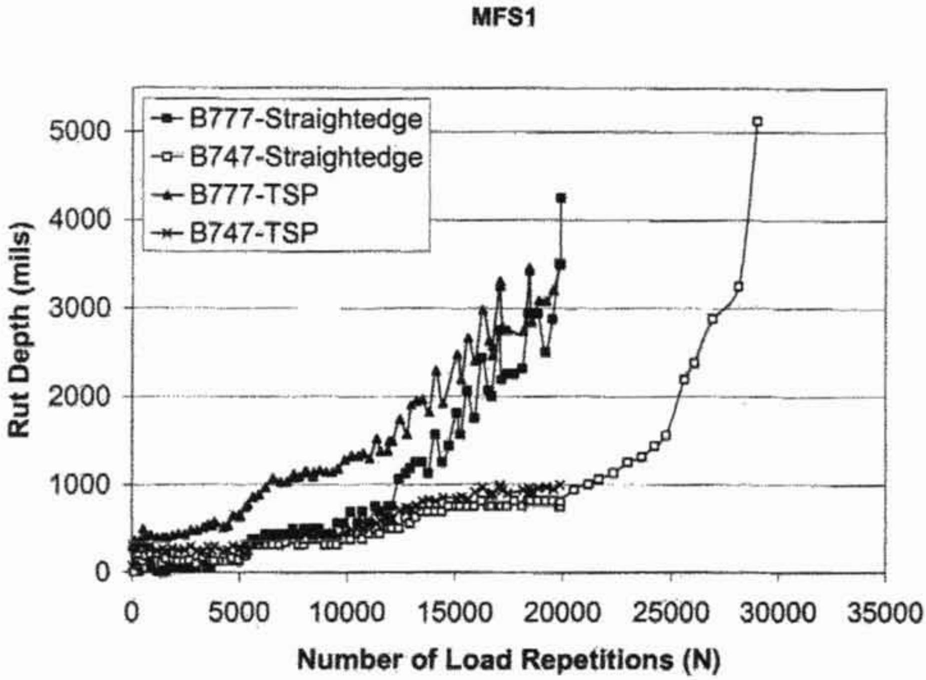


Figure 11. Comparison of Straightedge and TSP Rut Depths for MFC Test Section (1 mil = 0.0254 mm)



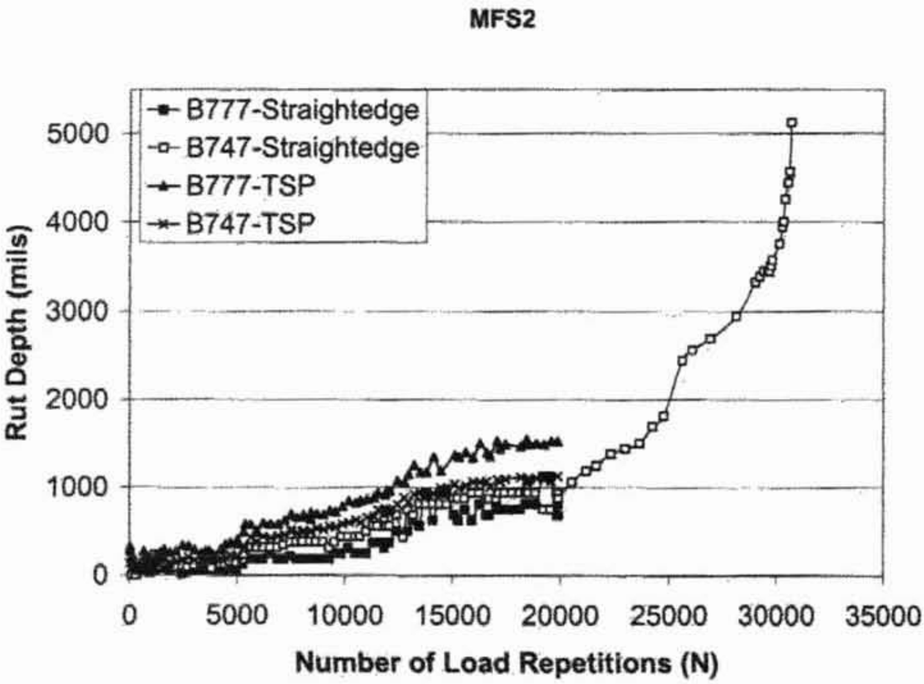


Figure 12. Comparison of Straightedge and TSP Rut Depths for MFS Test Section (1 mil = 0.0254 mm)

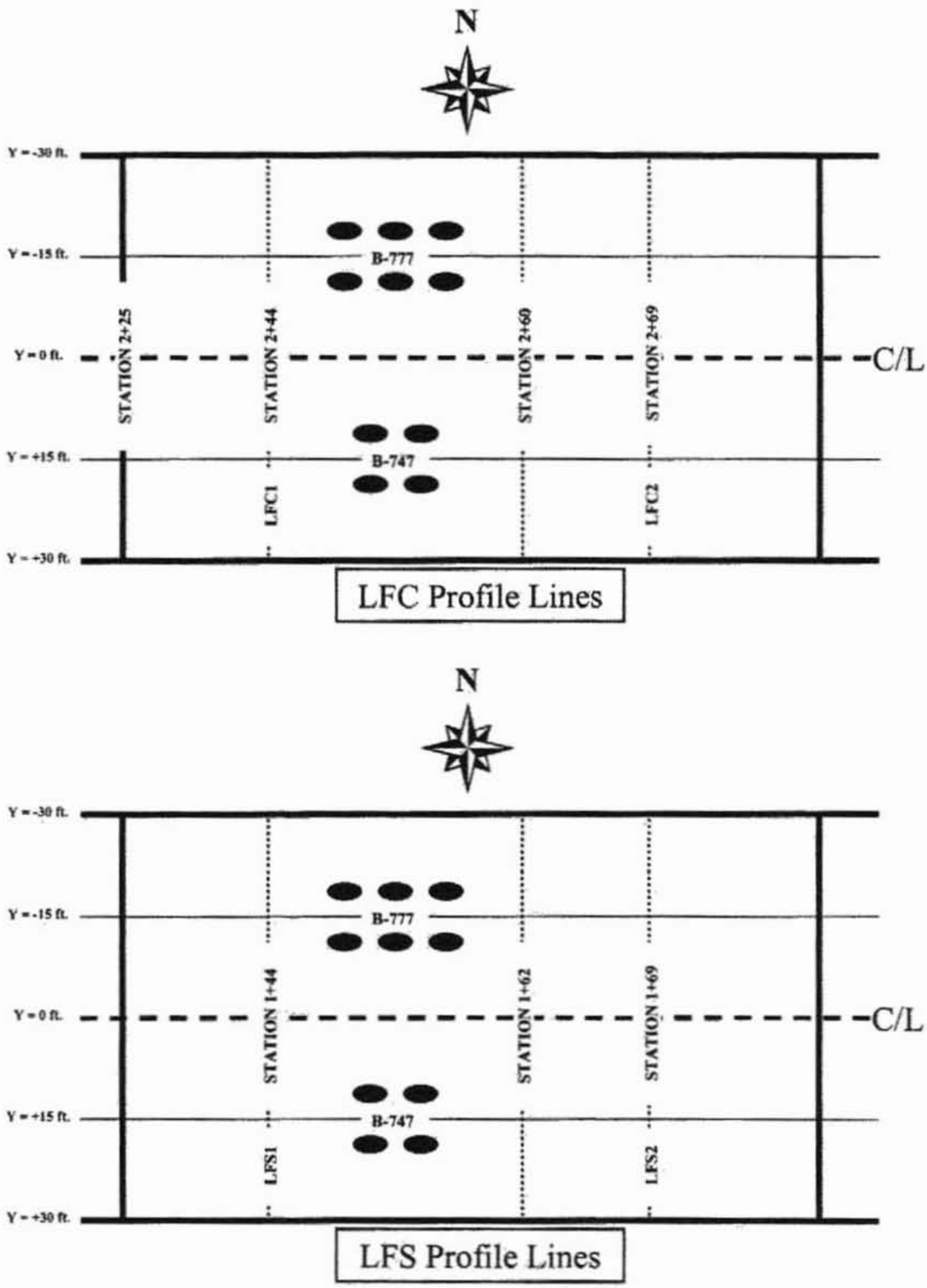
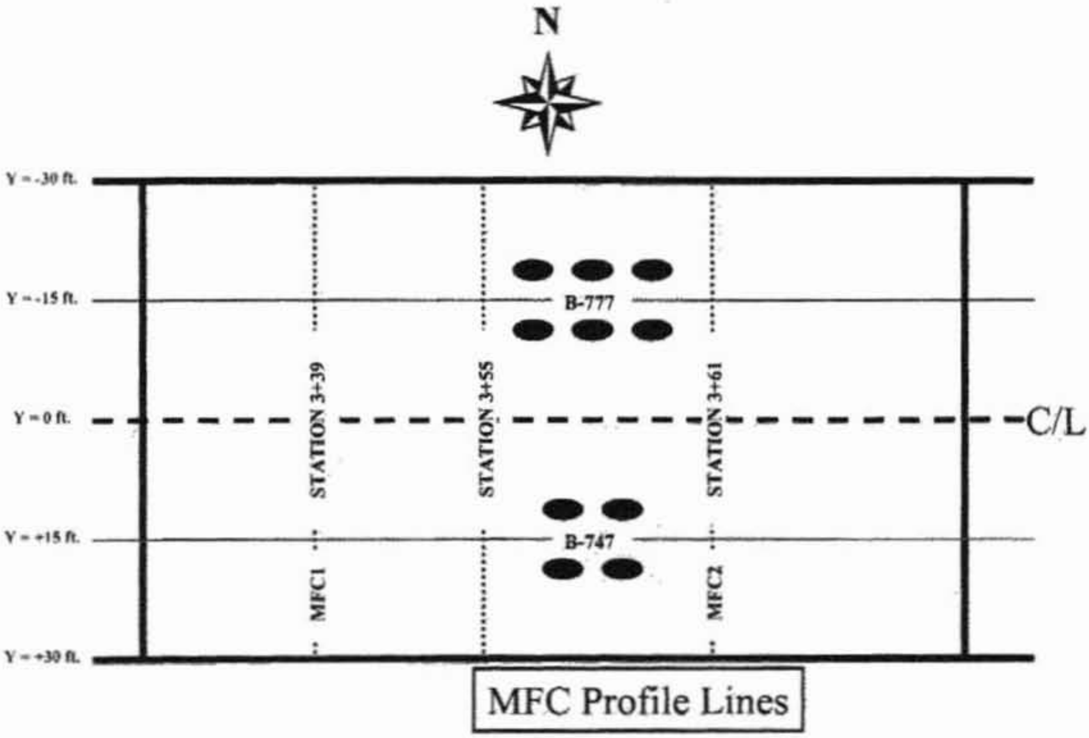


Figure 13. Location of Profile Lines for TSP Measurements in Low-Strength Test Sections (1 ft. = 0.305 m)



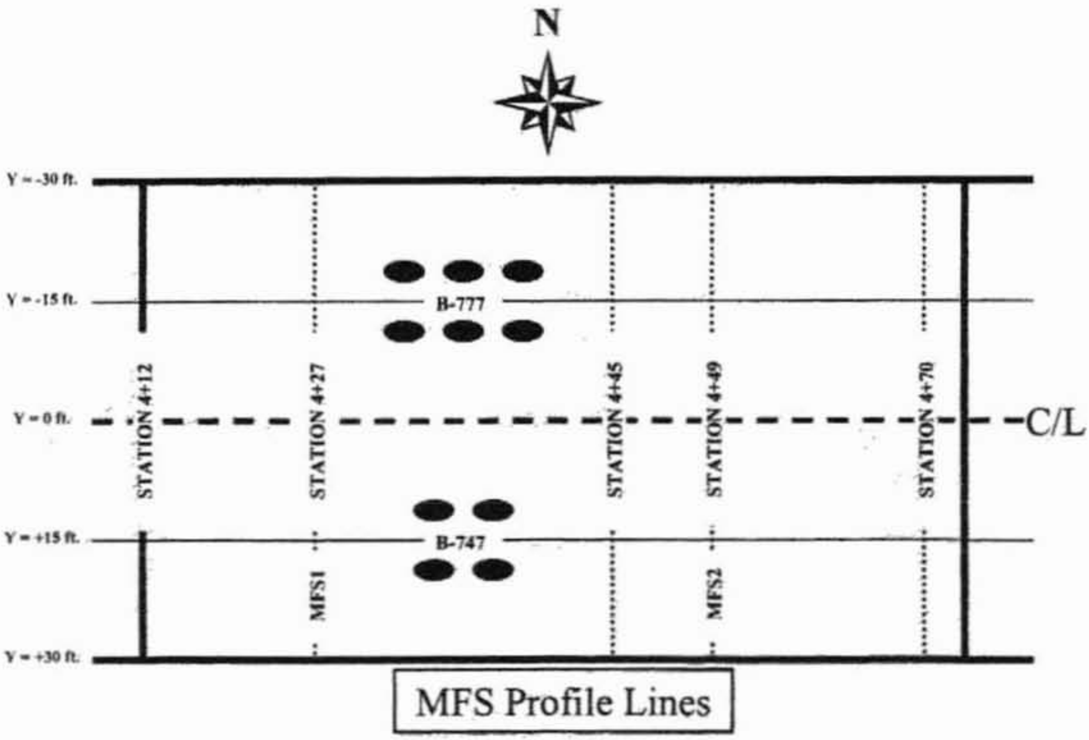
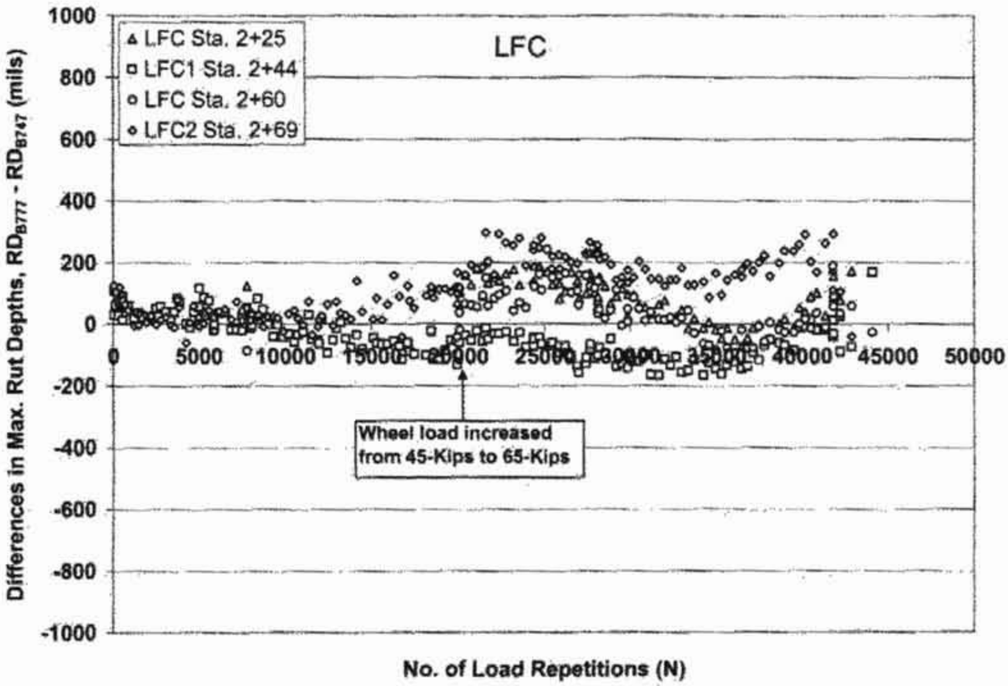


Figure 14. Location of Profile Lines for TSP Measurements in Medium-Strength Test Sections (1 ft. = 0.305 m)



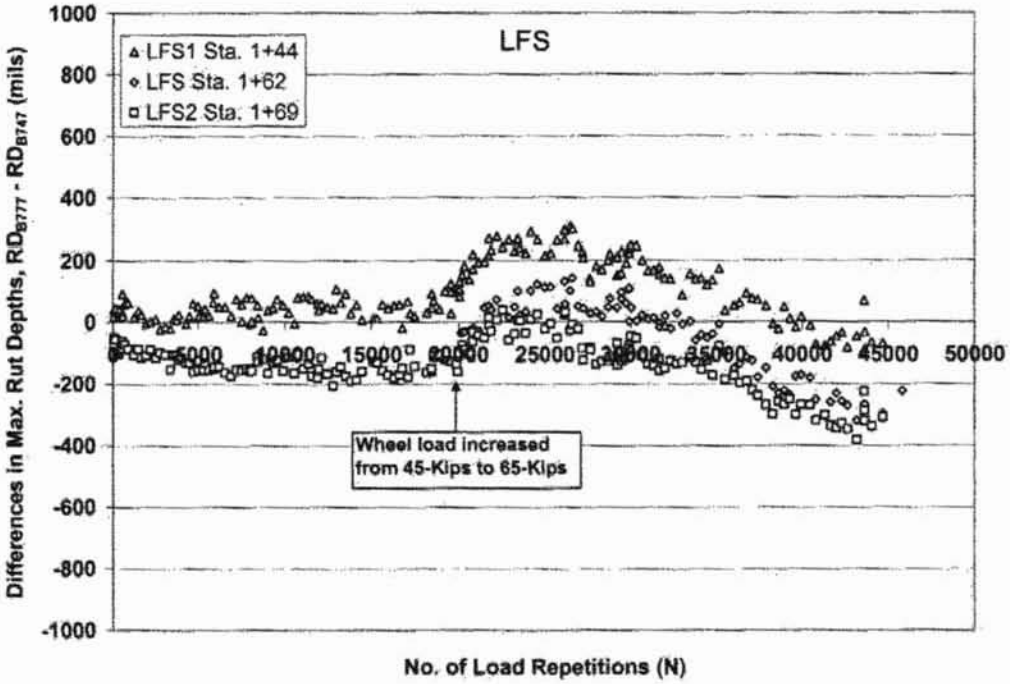
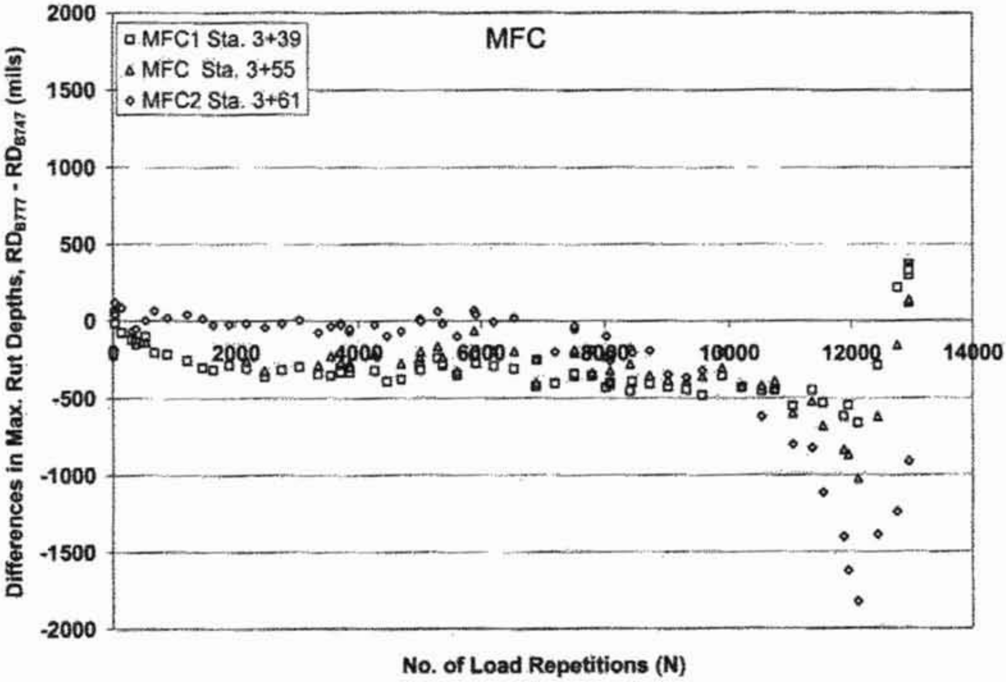


Figure 15. Differences in Maximum Rut Depths between B777 and B747 Trafficking for Low-Strength Test Sections (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)



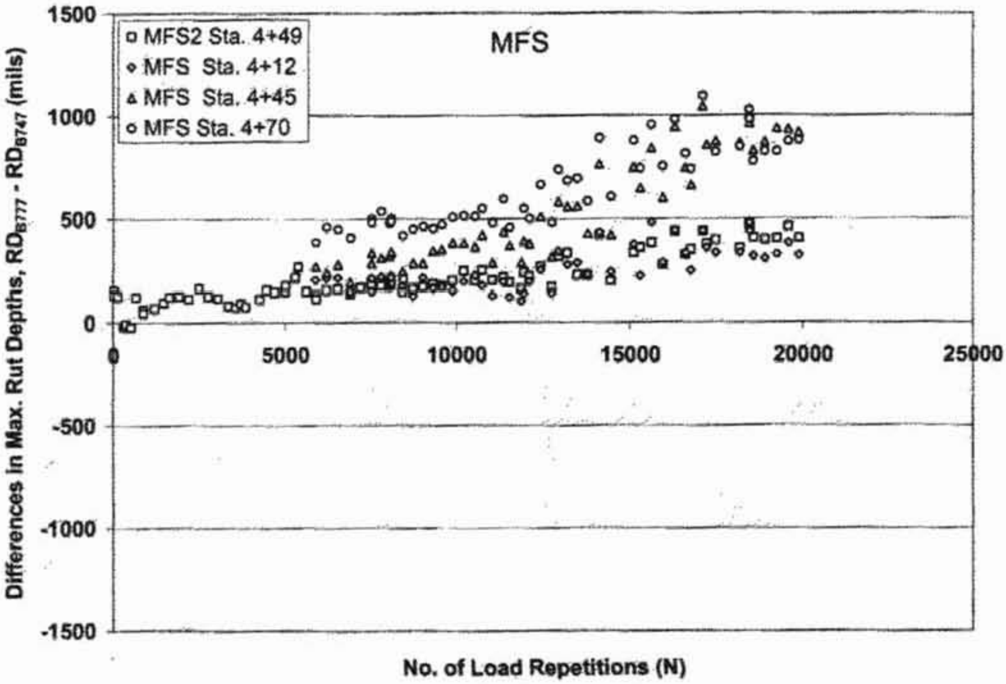


Figure 16. Differences in Maximum Rut Depths between B777 and B747 Trafficking for Medium-Strength Test Sections (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

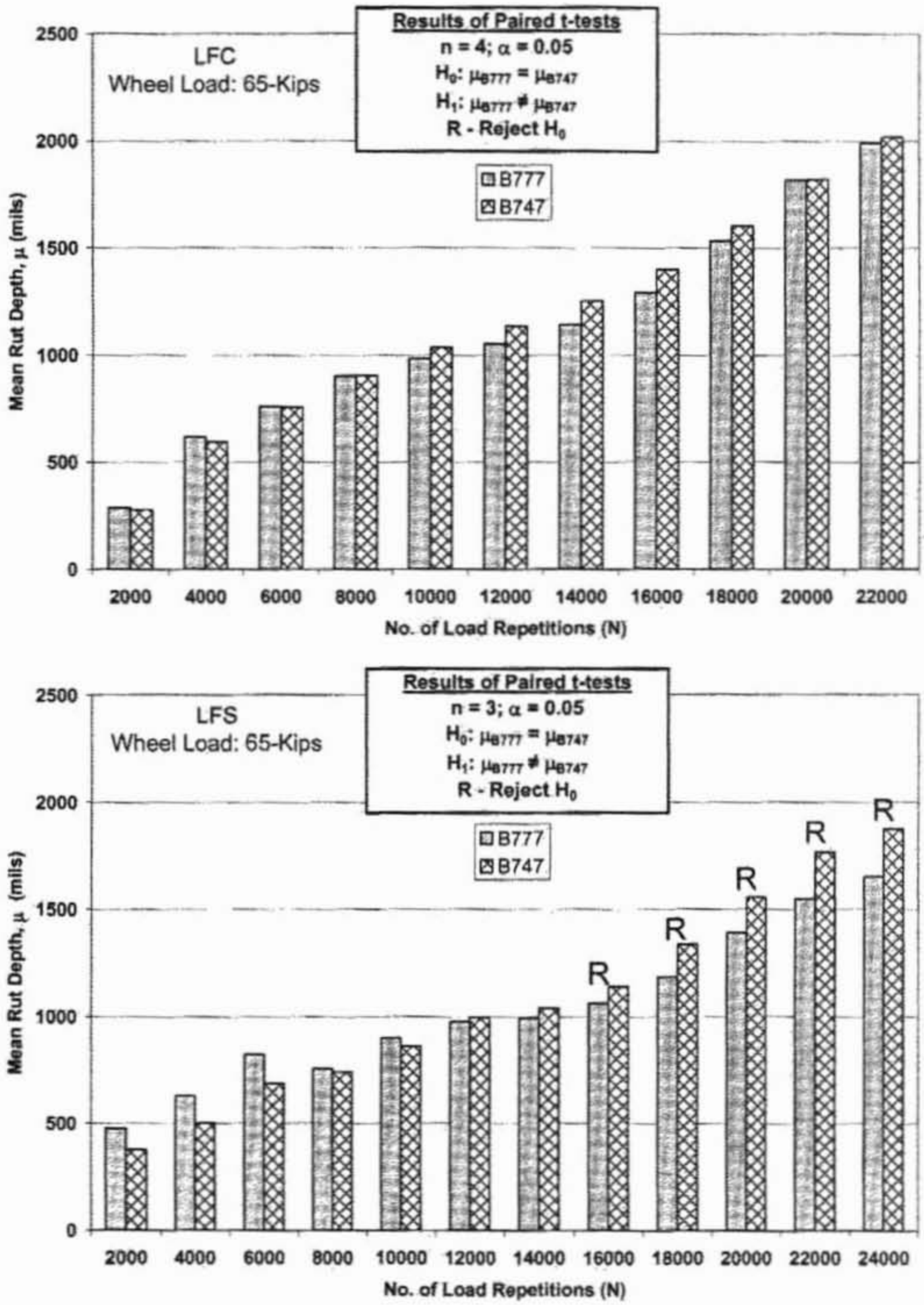


Figure 17. Results of Paired t-Tests between B777 and B747 Mean Rut Depths for Low-Strength Sections (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

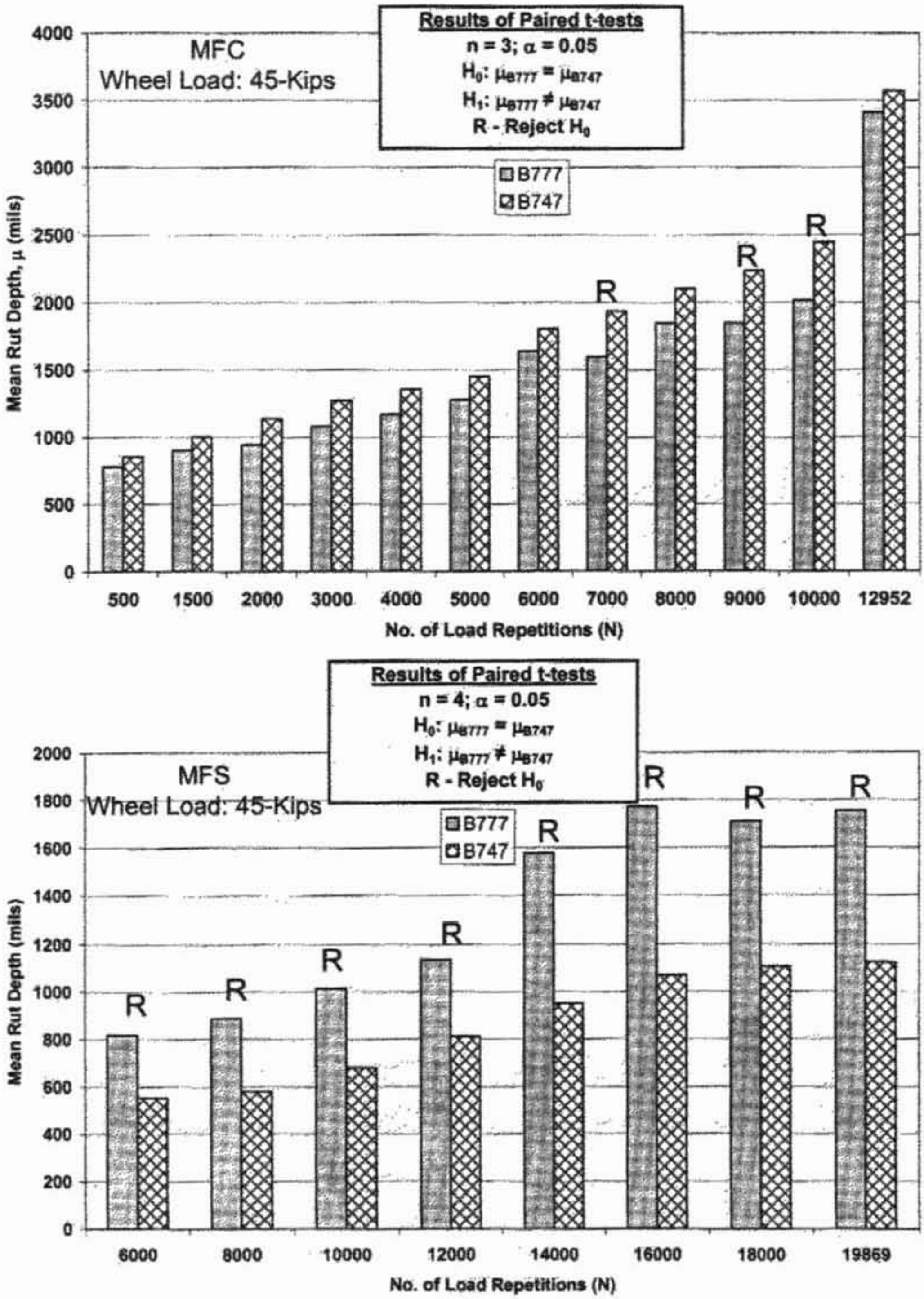


Figure 18. Results of Paired t-Tests between B777 and B747 Mean Rut Depths for Medium-Strength Test Sections (1 Kip = 0.45 tonnes; 1 mil = 0.0254 mm)

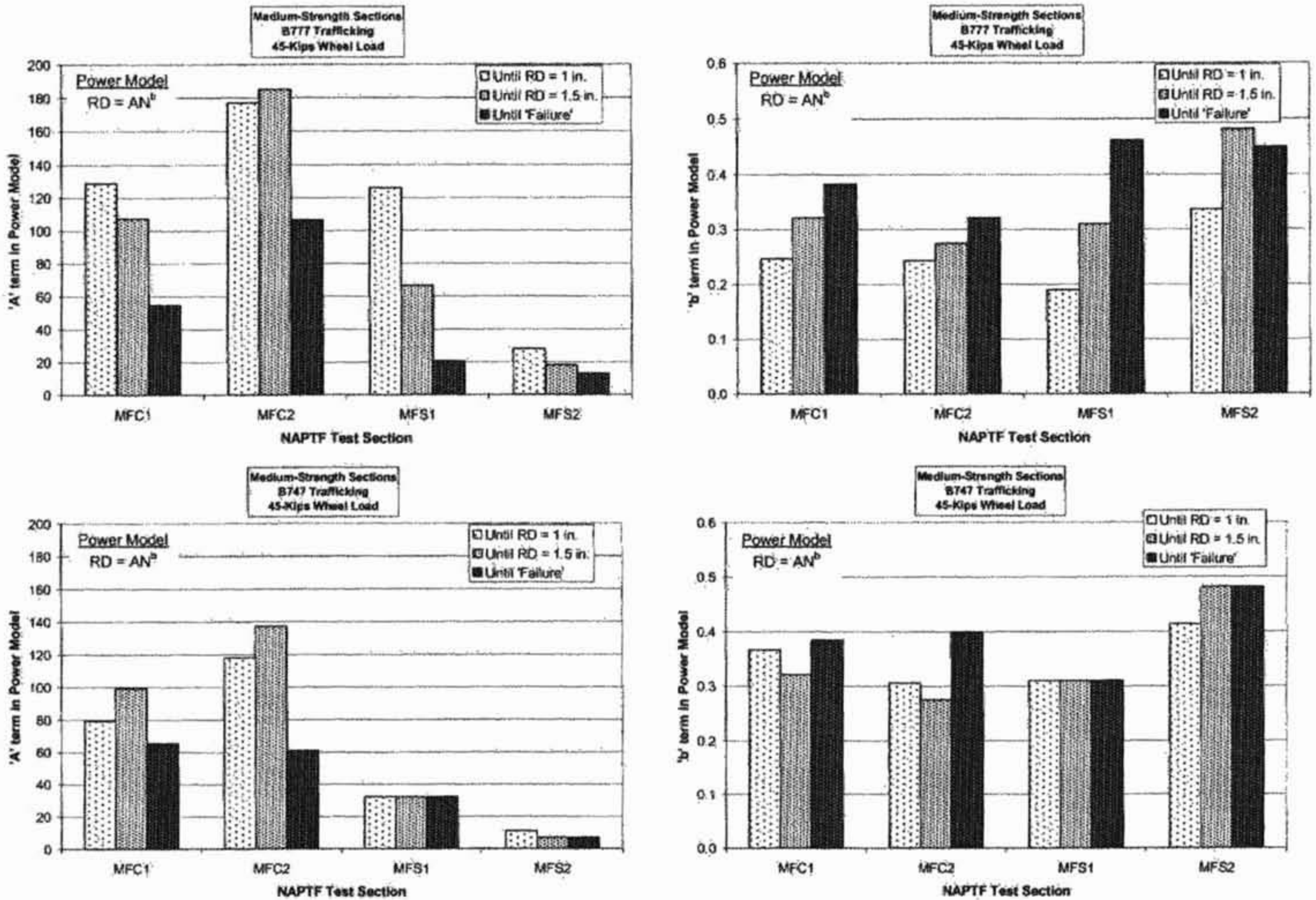


Figure 19. Comparison of Power Model Parameters for *Medium-Strength* Sections (1 Kip = 0.45 tonnes; 1 in. = 25.4 in)

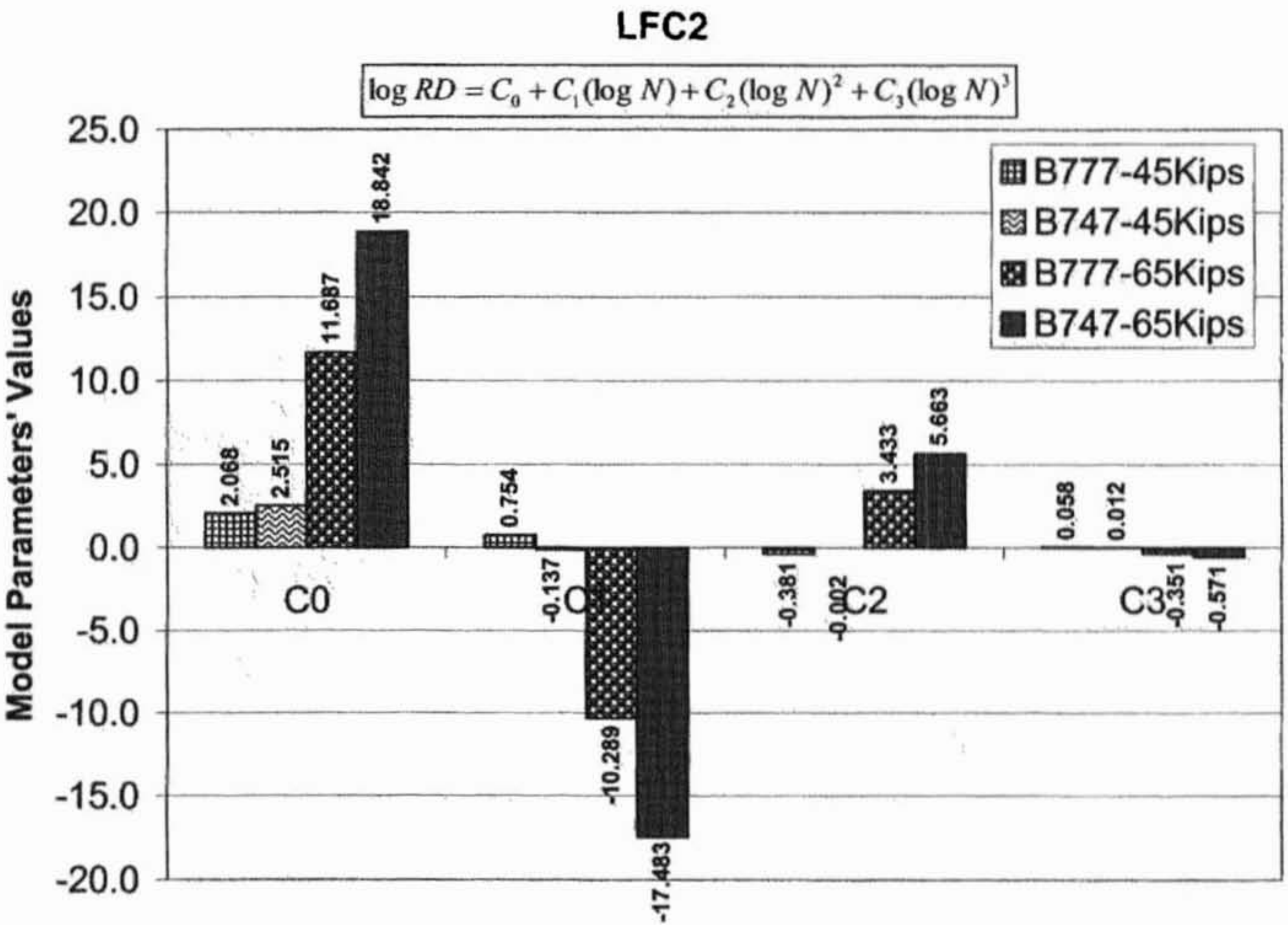


Figure 20. Variation in Third-Order Polynomial Model Paramters' Values (1 Kip = 0.45 tonnes)

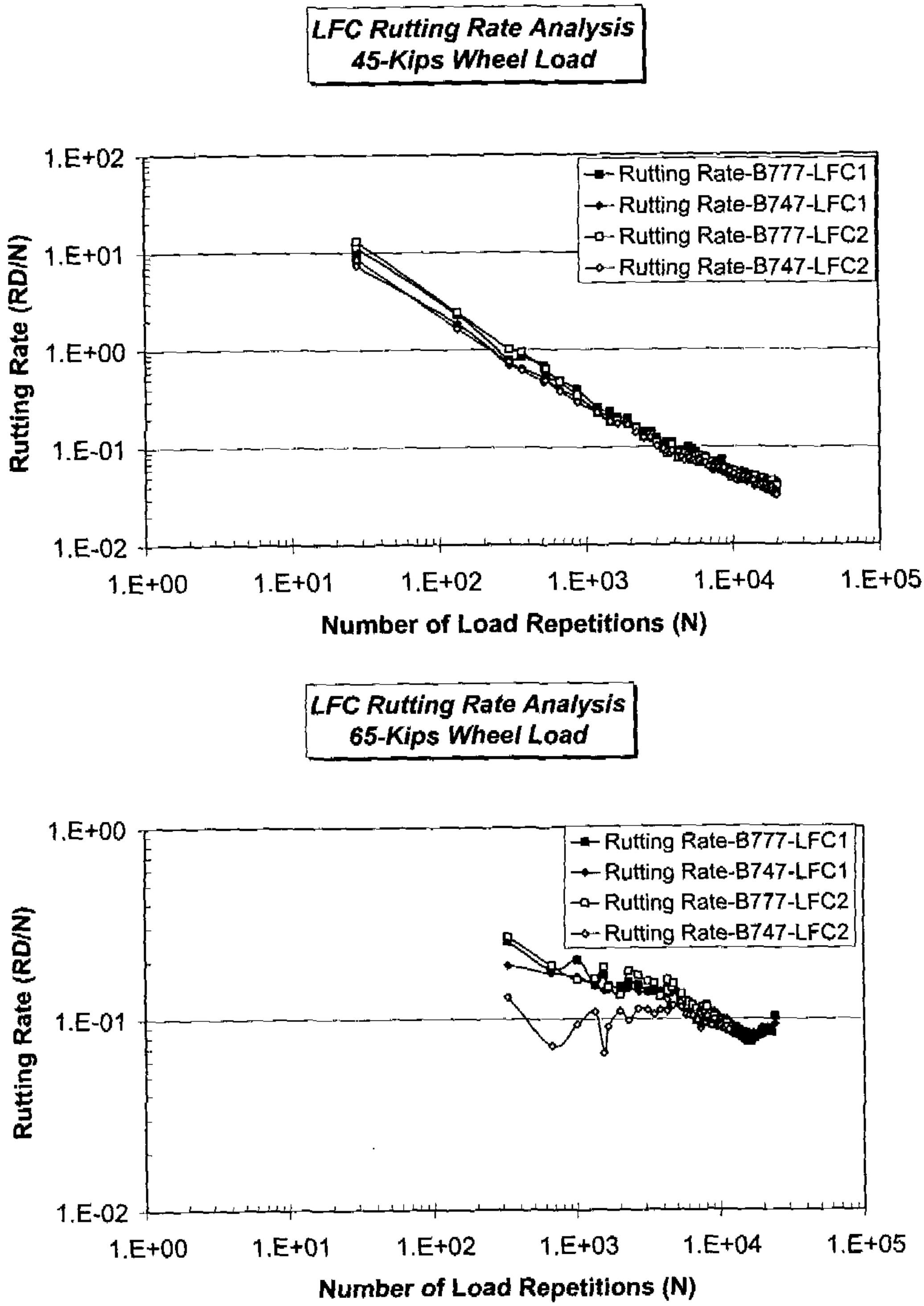
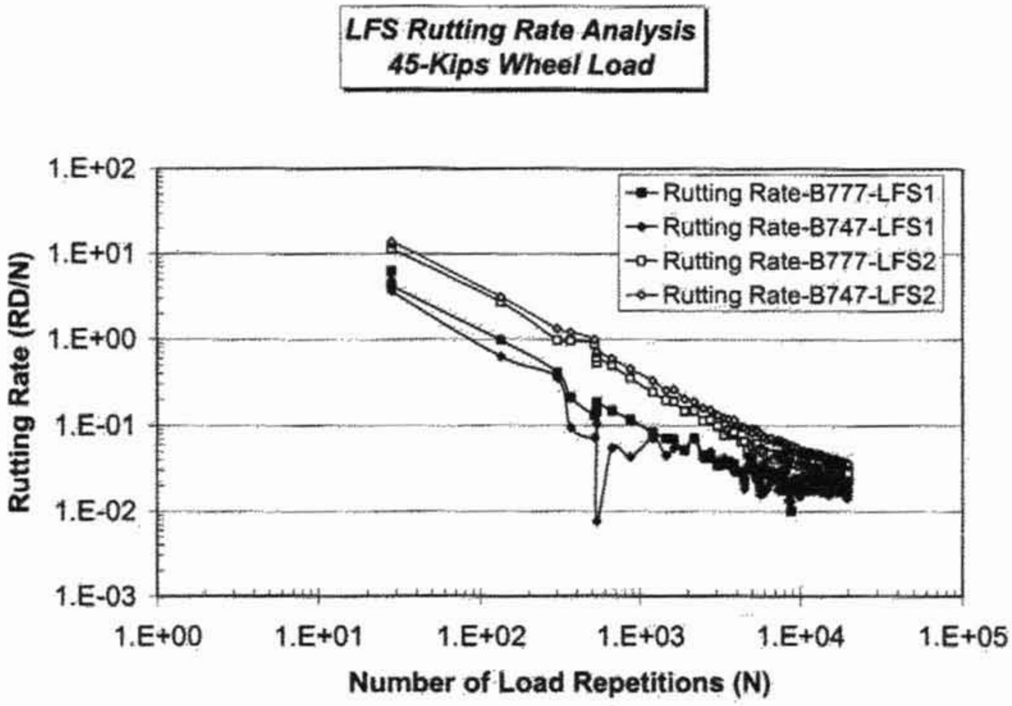


Figure 21. Rutting Rate (RR) Versus Number of Load Repetitions (N) for LFC Sections (1 Kip = 0.45 tonnes)



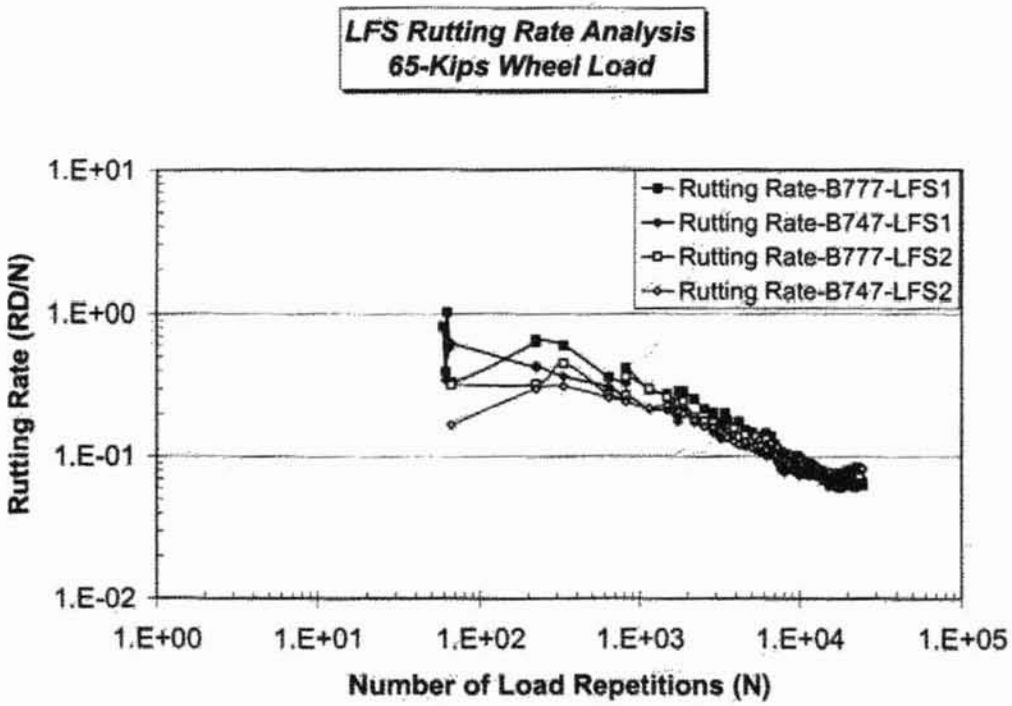
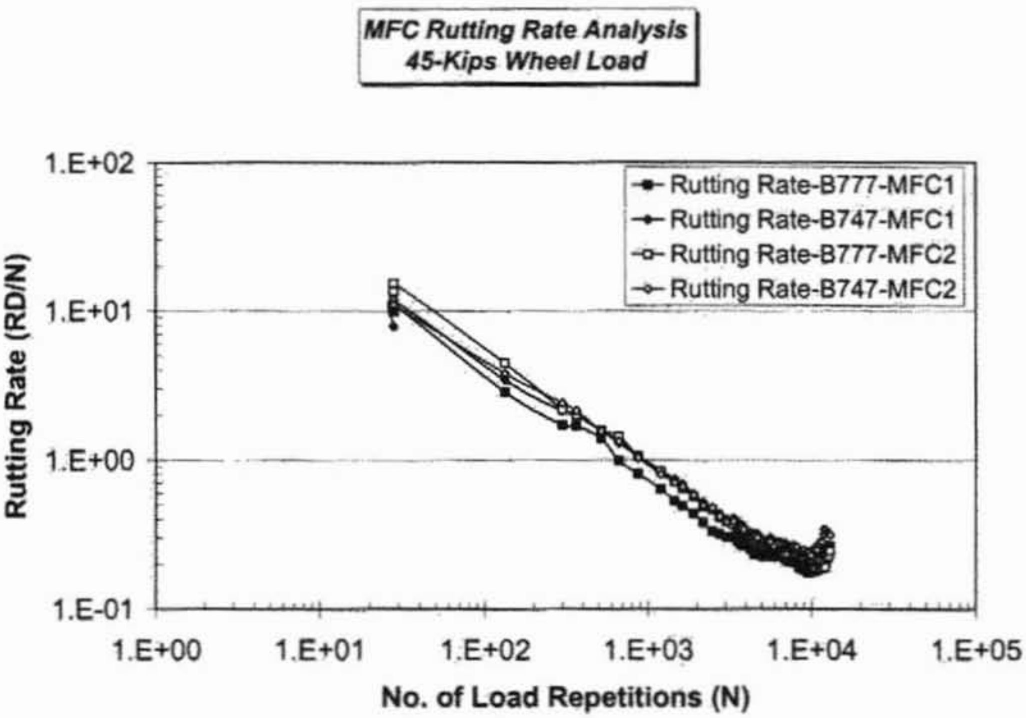


Figure 22. Rutting Rate (RR) Versus Number of Load Repetitions (N) for LFS Sections (1 Kip = 0.45 tonnes)



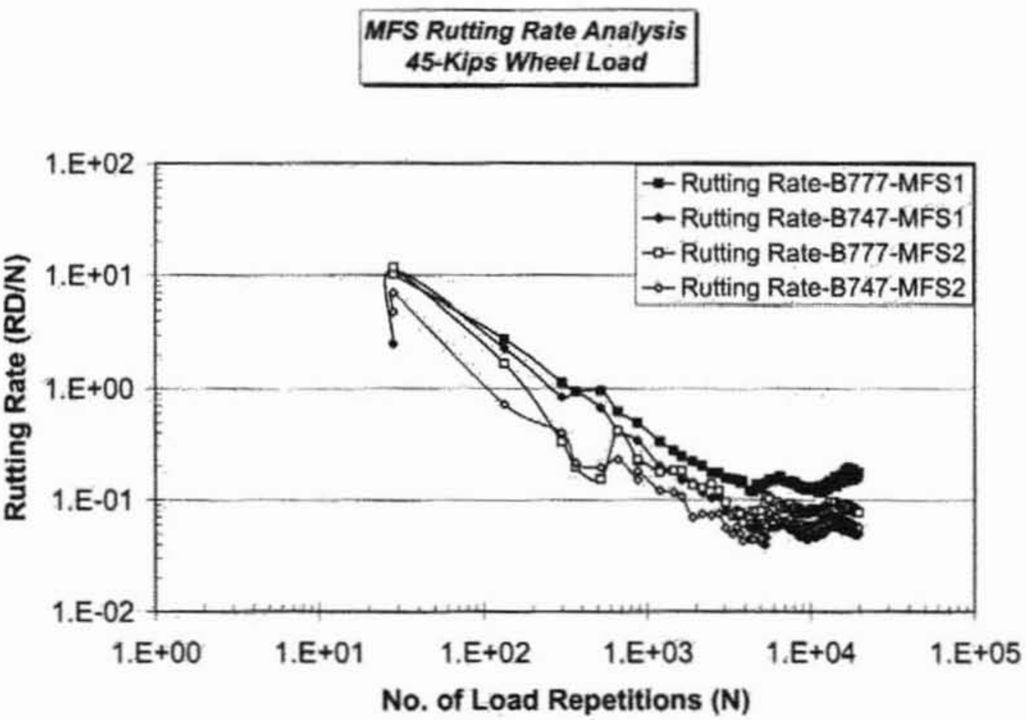


Figure 23. Rutting Rate (RR) Versus Number of Load Repetitions (N) for Medium-Strength Sections (1 Kip = 0.45 tonnes)