Designation: F1650 – 98 (Reapproved 2014)$^{\varepsilon 1}$

Standard Practice for Evaluating Tire Traction Performance Data Under Varying Test Conditions[1]

This standard is issued under the fixed designation F1650; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε[1] NOTE—Editorially corrected Subsection X2.4 in April 2014.

INTRODUCTION

Tire traction testing programs at proving grounds or other exterior test sites are often extended over a period of days or weeks. During this time period test conditions may change due to a number of varying factors, for example, temperature, rain or snow fall, surface texture, water depth, and wind velocity and direction. If tire performance comparisons are to be made over any part of the test program (or the entire program) where these test condition variations are known or suspected to affect performance, the potential influence of these variations must be considered in any final evaluation of traction performance.

1. Scope

1.1 This practice covers the required procedures for examining sequential control tire data for any variation due to changing test conditions. Such variations may influence absolute and also comparative performance of candidate tires, as they are tested over any short or extended time period. The variations addressed in this practice are systematic or bias variations and not random variations. See Appendix X1 for additional details.

1.1.1 Two types of variation may occur: time or test sequence "trend variations," either linear or curvilinear, and the less common transient or abrupt shift variations. If any observed variations are declared to be statistically significant, the calculation procedures are given to correct for the influence of these variations. This approach is addressed in Method A.

1.2 In some testing programs, a policy is adopted to correct all candidate traction test data values without the application of a statistical routine to determine if a significant trend or shift is observed. This option is part of this practice and is addressed in Method B.

1.3 The issue of rejecting outlier data points or test values that might occur among a set of otherwise acceptable data values obtained under identical test conditions in a short time period is not part of this practice. Specific test method or other outlier rejection standards that address this issue may be used on the individual data sets prior to applying this practice and its procedures.

1.4 Although this practice applies to various types of tire traction testing (for example, dry, wet, snow, ice), the procedures as given in this practice may be used for any repetitive tire testing in an environment where test conditions are subject to change.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E501 Specification for Rib Tire for Pavement Skid-Resistance Tests

E524 Specification for Smooth Tire for Pavement Skid-Resistance Tests

E826 Practice for Testing Homogeneity of a Metal Lot or Batch in Solid Form by Spark Atomic Emission Spectrometry

E1136 Specification for P195/75R14 Radial Standard Reference Test Tire

[1] This practice is under the jurisdiction of ASTM Committee F09 on Tires and is the direct responsibility of Subcommittee F09.20 on Vehicular Testing.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

F538 Terminology Relating to the Characteristics and Performance of Tires

3. Terminology

3.1 *Descriptions of Terms Specific to This Standard*—Descriptions of terms particular to this practice are listed either as principal terms or under principal terms as derived terms.

3.2 *Discussion:*

3.2.1 The terminology in this section is currently under review by Subcommittee F09.94 on Terminology. This terminology is subject to change and should be considered tentative.

3.2.2 *candidate tire (set), n*—a test tire (or test tire set) that is part of an evaluation program; each candidate tire (set) usually has certain unique design or other features that distinguish it from other candidate tires in the program.

3.2.3 *control tire (set), n*—a reference tire (or reference set) repeatedly tested in a specified sequence throughout an evaluation program, that is used for data adjustment or statistical procedures, or both, to offset or reduce testing variation and improve the accuracy of candidate tire (set) evaluation or detect test equipment variation, or both.

3.2.4 *reference tire (set), n*—a special test tire (test tire set) that is used as a benchmark in an evaluation program; these tires usually have carefully controlled design features to minimize variation.

3.2.5 *standard reference test tire, SRTT, n*— a tire that meets the requirements of Specification E1136, commonly used as a control tire or surface monitoring tire.

3.2.6 *surface monitoring tire (set), n*— a reference tire (or reference set), used to evaluate changes in the test surface over a selected time period.

3.2.7 *test, n*—a technical procedure performed on an object (or set of objects) using specified equipment, that produces data; the data are used to evaluate or model selected properties or characteristics of the object (or set of objects).

3.2.8 *test run, n—in tire testing*, a single pass (over a test surface) or sequence of data acquisition, or both, in the act of testing a tire or tire set under selected test conditions.

3.2.9 *test tire, n*—a tire used in a test.

3.2.10 *test tire set, n*—one or more tires, as required by the test equipment or procedure, to perform a test, producing a single set of results; these tires are usually nominally identical.

3.2.11 *traction test, n— in tire testing*, a series of *n* test runs at a selected operational condition; a traction test is characterized by an average value for the measured performance parameter.

4. Significance and Use

4.1 Tire testing is conducted to make technical decisions on various performance characteristics of tires, and good technical decisions require high quality test data. High quality test data are obtained with carefully designed and executed tests. However, even with the highest quality testing programs, unavoidable time or test sequence trends or other perturbations may occur. The procedures as described in this practice are therefore needed to correct for these unavoidable testing complications.

5. Summary of Practice

5.1 This practice specifies certain test plans for testing control tires. Testing begins with an initial test of the control tire or tire set. A number of candidate tire traction tests are then conducted followed by a repeat test of the control tire traction test. Additional candidate traction tests are conducted prior to the next control tire traction test. This sequential procedure is repeated for the entire evaluation program.

5.2 Using control tire average measured performance parameters, the performance parameters of the candidate tires (sets) are corrected for any changes in test conditions. Two correction procedures are described (Method A and Method B) that use different reference points for data correction and as such give different values for the corrected actual or absolute traction parameters. However, both test methods give the same relative ratings or traction performance indexes. See Section 10 for more details. The two test methods are summarized in more detail in Section 6 and Section 9. Both Methods A and B have advantages and disadvantages.

5.2.1 Method A uses the initial operational conditions defined by the first control traction test as a reference point. The calculations correct all traction test performance parameters (for example, traction coefficients) to the initial level or condition of the pavement or other testing conditions, or both. With this test method, corrections may be made after only a few candidate and control sets have been evaluated.

5.2.2 Method B uses essentially the midpoint of any evaluation program, with the grand average traction test value as a reference point. This grand average value is obtained with higher precision than the initial control traction test average of Method A, since it contains more values. However, Method B corrections cannot be made until the grand average value is established, which is normally at the end of any program.

5.3 Annex A1 provides illustrations of several types of typical variation patterns for control tire data. It additionally provides an example of the Method A correction calculations required to evaluate a set of candidate test tires. Method B corrections follow the same general approach as illustrated in Annex A1, with C_{avg} used in place of C1.

5.4 Annex A2 provides a recommended technique for weighting the correction of the two or three candidate values (for example, T1, T2, T3) between each pair of control values. This gives a slightly improved correction that may be important in certain testing operations.

5.5 Appendix X1 provides a statistical model for the traction measurement process. This may help the user of this practice to sort out the differences between fixed or bias components of variation and random components of variation. Appendix X1 gives a rationale for the procedures as outlined in this practice.

5.6 Annex A2 contains some background and details on the propagation of error or test variation that occurs when corrections are applied to the measured traction performance parameters and when traction performance indexes are calculated.

METHOD A—DATA CORRECTIONS BASED ON INITIAL CONTROL TRACTION TEST

6. Summary of Method A

6.1 This method corrects the data obtained throughout the evaluation program to the initial conditions (test surface or other, or both)" reference point" at the beginning of the program. The correction procedure (and calculation algorithm) for time trend variations is mathematically equivalent to that described in Practice E826. The procedure used for abrupt or step changes is provisional and is subject to change as experience is gained. In this method the initial traction test value for the control tire is a key data point. This method also allows for decisions on the need for any correction, based on a statistical analysis of the control tire data.

7. Procedure

7.1 The test procedure is given in terms of testing tire sets of four tires, that is, one tire on each of four vehicle positions. If only one tire is to be tested (trailer or other dynamometer vehicle testing), follow the procedure as outlined with the understanding that the one tire replaces the tire set.

7.2 Assemble all the tire sets to be tested in any evaluation program or for daily testing. Select the test speeds to be used and other operational test conditions as well as the order in which the candidate tire sets are to be tested.

7.2.1 For any selected order, a test plan is established with reference tire(s) designated as a control tire set tested at regular intervals among the selected candidate sets. Select the number of test runs or replicates for both control and candidate tire sets. A complete test for a tire set is defined as the total of *p* traction tests, one at each selected operational test condition, with *n* replicate test runs for each operational condition (for example, speed and surface type).

7.2.2 Tests with a surface monitoring tire may also be conducted on a regular basis in addition to the control tire.

7.3 *Test Sequence*—The control tires may be standard tires as specified in Specifications E501, E524, and E1136, or a tire set similar in design and performance level to the candidate sets. Conduct a complete test for the control sets in relation to the candidate sets as given in Table 1. Two test plans are given: Plan A, in which (excluding the initial control set) candidate tires constitute 67 % of the tires tested, and Plan B, in which candidate tires constitute 75 % of the tires tested.

TABLE 1 Test Plans for Tire Performance Evaluation[A]

Plan A:
Test in the order: C1, T1, T2, C2, T3, T4, C3, T5, T6, C4, etc.
Plan B:
Test in the order: C1, T1, T2, T3, C2, T4, T5, T6, C3, T7, T8,T9, C4, etc.

[A] *Ci* = average measured parameter (for *n* test runs) for a selected operational condition for the *i*th control set test (that is, *i* = 1, 2, 3, etc.)

Ti = average measured parameter (for *n* test runs) of a selected operational condition for the *i*th candidate set test (that is, *i* = 1, 2, 3, etc.).

7.4 *Number of Test Runs at Each Speed or Operational Condition*—The number of test runs or replicates, *n*, for each speed or other selected operational condition for each candidate tire set and each control set, except the first set, shall be selected. The number of test runs depends on the test method. Good testing procedure calls for as many test runs as possible. If direction of test is important on any test surface, one half of the test runs shall be in each direction.

7.4.1 *Number of Test Runs: Initial Control Set*—The initial test for the control, indicated by C1, is a key value used for correction of candidate set performance parameter values as testing proceeds. Therefore, the average performance parameters for C1 must be evaluated with a high degree of confidence and the recommended number of test runs for C1 should be at least two times the number of test runs selected in 7.4.

7.4.2 *More than One Control Tire*—In some types of testing, the control tire is damaged or changed by the testing to the extent that it ceases to function as a stable control. In such situations it is necessary to use more than one control tire throughout any evaluation program. In such cases a control tire indication scheme such as C1-1, C1-2, C1-3, C2-4, C2-5, C2-6, C3-1, etc., is suggested. In this scheme, C1-1 = control tire 1, sequence use 1; C1-2 = control tire 1, sequence use 2; ... ., C2-4 = control tire 2, sequence use 4, etc.

7.5 *Table of Results*—Prepare a table of test results and record all data with columns for:

7.5.1 Test sequence number, a sequential indication from 1 to *m*, of all the tests for any program of evaluation,

7.5.2 Tire set identification,

7.5.3 Speed or other selected operational test condition(s), and

7.5.4 Average value (for *n* test runs) for the measured parameter for that operational condition.

7.6 Both control and candidate set data shall be included in the table in the order as tested. If deemed important, a separate table of ambient temperature, wind direction, wind velocity, or other weather information also shall be prepared on a selected time (hourly) basis.

8. Calculations for Corrected Traction Performance Data

8.1 *Preliminary Control Set Data Review*—The decision to correct data, for any part of the test program where candidate set comparisons are to be made, is based on the time or test sequence response of the control tire parameters for each speed or other selected operational test condition. Corrections may also be made for the entire test program. If a significant trend is found or if significant transient perturbations are found, corrections are made for candidate set traction performance parameters.

8.2 *Evaluating the Control Tire Data*—Using the data table(s) generated in accordance with the procedures outlined in 7.5, plot the average control tire traction test parameter (that is, for C1 to Ci) at each speed or other operational condition, as a function of the test sequence number for the control set or the "test time" period (hours) that has elapsed for each control test. For a good evaluation of potential drift, at least five control set values (that is, C1 to C5 as defined in Table 1) should be available; six or more is better.

8.2.1 The plot of average control traction test parameter versus test sequence number or time period is examined for two types of response: (*1*) any upward or downward drift or trend and (*2*) the less common occurrence of any transient or step change of either a temporary or permanent value shift. Annex A1 gives some typical control tire versus test sequence number plots. Since the time drift may be nonlinear, a transformation may be applied to the data to permit a linear regression analysis to be conducted. A curvilinear time trend can be converted into a relationship that very closely approximates linearity on the basis of the logarithmic transformation of both the test sequence number and the average parameter test value.

8.2.2 The calculated correlation coefficient, $R_{(calc)}$, from the transformed data linear regression analysis is used to determine if the trend or drift is significant. If the calculated coefficient is significant, a correction of the candidate set traction parameter values is made. Correction for any significant drift is made on a basis that allows for any overall curvilinear trend (see 8.5).

8.3 *Evaluating the Significance of Drift*—For the linear or log transformed traction parameter versus linear or log transformed test sequence number plot, evaluate the correlation coefficient, $R_{(calc)}$, using any typical software or spreadsheet statistical calculation algorithm.

8.3.1 Determine if $R_{(calc)}$ is significant for the control tire traction parameter by referring to Table 2, a table of 95 % confidence level "critical" correlation coefficient values, $R_{(crit)}$, for varying degrees of freedom (DF). If the calculated correlation coefficient is greater than the tabulated critical value, the calculated coefficient is significant and corrections are applied to the candidate tire data in accordance with 8.5.

8.3.2 If the correlation coefficient is not significant, no corrections are required and the original candidate tire set performance data may be used for evaluation.

TABLE 2 Critical Values of Correlation Coefficient[A]

DF	R(crit)
1	0.997
2	0.950
3	0.878
4	0.811
5	0.754
6	0.706
7	0.666
8	0.631
9	0.602
10	0.576
12	0.532
14	0.497
16	0.468
18	0.443
20	0.422
25	0.380
30	0.349

[A]Critical values for the correlation coefficient, R(crit) at the 95 % confidence level or at $p = 0.05$ are given as a function of the degrees of freedom, DF. The value for DF is equal to ($N - 2$), where N is the number of pairs of data, number of log (average parameter) values, plotted for the control set, that is, Ci.

8.4 *Evaluating the Significance of Transient Variations*—The procedure outlined for a decision on the existence of a transient or shift variation is given as a recommended approach. Transient variations are one of two types: (*1*) After several control values with an established trend, an abrupt change in one or more control traction parameter values occurs (this is followed by a return to the established trend); or (*2*) after an established trend is observed, an abrupt shift occurs and a new trend is established with no return to the original level.

8.4.1 The significance of the shift is established by comparing the magnitude of the step with the standard error of the estimate (or the standard deviation) of the control traction values about the regression line. Calculate the standard error of the estimate (SE) for the actual or log transformed data (see 8.2 and 8.3) according to the type of transient shift. All of the calculations as outlined below must be performed on the same basis, that is, all with actual values or all with transformed values.

8.4.2 *For a Type 1 Shift*—With any typical statistical software, calculate the SE for the regression line fitted to all the data points, omitting the shifted or transient offset points. Designate this as SE(MR), the main regression standard error of estimate. If there are several (four or more) offset points, calculate the SE for the regression line fitted to these points. Designate this as SE(O), the offset point standard error of estimate. If there are three or fewer offset points, calculate their average; designate this as OP_{avg}.

8.4.3 *For a Type 2 Shift*—With any statistical software, calculate the SE of each of the two regression trend lines (actual values or transformed). Designate these as SE(1) for the first trend line and SE(2) for the second line.

8.4.4 *Significance of Transient Shift*—The significance is determined by comparing the magnitude of the shift or offset with the magnitude of the standard errors in question.

8.4.4.1 *Significance For a Type 1 Shift*—If there are four or more offset points, the shift is significant if the difference between the offset regression line and the main regression line (at the shift point) is greater than the sum [2 SE(MR) + 2 SE(O)], that is, greater than the sum of the two standard deviation limits (2 σ limits) about each regression line. If there are three or fewer offset points, the shift is significant if the difference between OP_{avg} and the value of the regression line at the initial point of offset is greater than [4 SE(MR)].

8.4.4.2 *Significance For a Type 2 Shift*—The shift is significant if the difference between the two regression lines at the point of initial offset is greater than the sum [2 SE(1) + 2 SE(2)].

8.4.5 If significant transient shifts are found, corrections are made in accordance with 8.5.

8.5 *Making the Corrections*—For each speed or other operational condition, arrange the control set average (measured) traction test values in chronological or test sequence order, that is, C1, C2, C3, ... Ci. Normal correction procedure is defined on the basis of equivalent corrections to each candidate tire in the interval between two successive control tire traction tests (see 8.5.1). An alternative correction procedure using a weighting technique for the first and second candidate tires between successive control tires (Plan A) or the first, second, and third (Plan B), is given as an option in Annex A2. This optional correction procedure may be more important for Plan B testing with three candidate tires between each successive set of control tires. For the normal procedure, compute the "correction" factors, Fj, as follows:

$$F1 = (C1 + C2)/2C1$$
$$F2 = (C2 + C3)/2C1$$
$$F3 = (C3 + C4)/2C1$$
$$F4 = (C4 + C5)/2C1 \quad (1)$$
$$F5 = (C5 + C6)/2C1$$
$$\ldots$$
$$Fj = (Ci + Ci + 1)/2C1$$

8.5.1 Divide the measured candidate set performance parameter values by the appropriate "correction" factor to obtain the "corrected value" for the candidate set performance parameter. The appropriate correction factor is that factor calculated from the control (C values) that brackets the measured candidate parameter values within the test sequence (time) span for the two C values. Thus, apply the Factor F1 to the candidate test values between C1 and C2; apply F2 to the candidate test values between C2 and C3, etc. The following equations give the general expression for the" corrected parameter" values for Plan A, in terms of the measured parameter values and the value of Fj. Expressions for the other "corrected parameter" values have the same calculation procedure, for example:

(Corr) Parameter Candidate Set 1 =
"as measured" Parameter Candidate Set1/F1

(Corr) Parameter Candidate Set 2 =
"as measured" Parameter Candidate Set2/F1

(Corr) Parameter Candidate Set 3 = (2)

"as measured" Parameter Candidate Set3/F2

(Corr) Parameter Candidate Set 4 =
"as measured" Parameter Candidate Set4/F2

…

(Corr) Parameter Candidate SetM =
"as measured" Parameter Candidate SetM/Fj

8.5.2 Tabulate the corrected candidate parameter values as an additional column in the table format as outlined in 7.5. Indicate on the table that Method A correction was used.

METHOD B—CORRECTIONS BASED ON AVERAGE OF CONTROL TRACTION TESTS

9. Summary of Method B

9.1 This method corrects the data obtained throughout the evaluation program using the same basic calculation algorithm as for Method A, with one important difference. The candidate tire traction values are corrected to a "reference point" characterized by the grand average traction test value (averaged over *all* control tire traction test values). This method also applies the corrections to all candidate tire traction test data values. No statistical tests of significance for trends or transient shifts are required. See Appendix X2 for some background on how making corrections influences the ±2 σ limits on candidate tire relative performance as outlined in Section 10.

9.2 The test procedure for Method B is exactly as given in Section 7 of this practice. Follow all instructions as given in this section.

9.3 *Making the Corrections*—For each speed or other operational condition, arrange the control set average (measured) traction test values in chronological or test sequence order, C1, C2, C3, ... Ci. Compute the "correction" factors, Fj, as follows:

$$F1 = (C1 + C2)/2C_{avg},$$
$$F2 = (C2 + C3)/2C_{avg},$$
$$F3 = (C3 + C4)/2C_{avg},$$
$$F4 = (C4 + C5)/2C_{avg}, \quad (3)$$
$$F5 = (C5 + C6)/2C_{avg},$$
$$\ldots$$
$$Fj = (Ci + Ci + 1)/2C_{avg}$$

where:

C_{avg} = average of all Ci values in any program.

9.3.1 Divide the measured candidate set performance parameter values by the appropriate "correction" factor to obtain the "corrected value" for the candidate set performance parameter. The appropriate correction factor is that factor calculated from the control (C values) that brackets the measured candidate parameter values within the test sequence (time) span for the two C values. Thus, apply the Factor F1 to the candidate test values between C1 and C2; apply F2 to the candidate test values between C2 and C3; etc. The following equations give the general expression for the" corrected parameter" values for Plan A in terms of the measured parameter values and the value of Fj. Expressions for the other "corrected parameter" values have the same calculation procedure:

(Corr) Parameter Candidate Set 1 =
"as measured" Parameter Candidate Set1/F1,

(Corr) Parameter Candidate Set 2 =
"as measured" Parameter Candidate Set2/F1,

(Corr) Parameter Candidate Set 3 = (4)

"as measured" Parameter Candidate Set3/F2, and

(Corr) Parameter Candidate Set 4 =
"as measured" Parameter Candidate Set4/F2,

…

(Corr) Parameter Candidate SetM =
"as measured" Parameter Candidate SetM/Fj

9.3.2 Tabulate the corrected candidate parameter values as an additional column in the table format as outlined in 7.5. Indicate in the table that Method B correction was used.

10. Calculations for Relative or Comparative Performance Evaluation

10.1 the uncorrected or corrected traction parameters for Method A and to the corrected traction parameters of Method B. Once the calculations for correcting the absolute traction performance data are completed, relative or comparative performance among any selected group of candidate tire sets may be evaluated.

10.1.1 Select one set of tires to act as a reference standard tire. This may be a control tire set or a special candidate set. Calculate the traction performance index, TPI, for each of the candidate tire sets according to Eq 5 using either corrected traction performance data if corrections were made, or original data if no corrections were made. The traction performance index, TPI, is an index where higher values indicate improved or superior performance compared to lower TPI values. Therefore, TP parameter values used in Eq 5 should reflect this performance characteristic. If certain measured performance parameters are used, such as stopping distance, where lower values indicate superior traction performance, then an inverse relationship is required for Eq 5, that is, invert the ratio in the brackets.

$$\text{TPI} = [\text{TP parameter } (i)/\text{TP parameter } (\text{ref std})]100 \quad (5)$$

where:

TP parameter (i) = corrected or original average traction performance parameter for the test for candidate set (i), and

TP parameter (ref std) = corrected or original average traction performance parameter for the test for the selected reference standard tire.

10.1.2 Tabulate the TPI values as an additional column in the table format as described in 7.5.

11. Citing This Practice

11.1 When this practice is cited in any particular traction or other similar tire test standard, the following information shall be given to adequately describe the correction procedure that was utilized.

11.1.1 The citation shall be in either of the following formats:

$$\text{Format 1: F1650} - \text{A or F1650} - \text{B} \quad (6)$$

where:

A = Method A used; B = Method B used,

or

$$\text{Format 2: F1650} - \text{AW or F1650} - \text{BW} \quad (7)$$

where:

W indicates that the optional weighting technique was used.

12. Keywords

12.1 data correction; test variation; testing trends; traction testing

ANNEXES

(Mandatory Information)

A1. TYPICAL VARIATIONS OF CONTROL TIRE DATA AND AN EXAMPLE OF CORRECTION CALCULATIONS FOR CANDIDATE SET WET TRACTION EVALUATION

A1.1 *Typical Control Tire Data Response*—Figs. A1.1-A1.5 illustrate typical test sequence number responses for control tire data. Wet traction coefficient data are shown in the illustrations for one typical test speed.

A1.1.1 Fig. A1.1 is a plot for a zero slope response, that is, no trend, that has a low standard error of the estimate (standard deviation of the points about the fitted line), SE, and indicates relatively good test precision across the indicated test period. The SE expressed as a coefficient of variation, CV, (relative to average traction level) is 1.5 %. Fig. A1.2 is a similar plot also with no trend but poorer test precision, that is, much greater scatter of the points about the fitted zero slope line with an SE (on CV basis) of 3.8 %.

A1.1.2 Fig. A1.3 illustrates a typical transient or step shift in control tire data in the middle of the test period. Such a shift might result from a substantial inadvertent reduction in water depth for higher speed wet traction testing, with a return to initial water depth near the end of the test period. The comparatively good fit of the other four points at the 0.50 traction coefficient level constitutes a base level for point fit

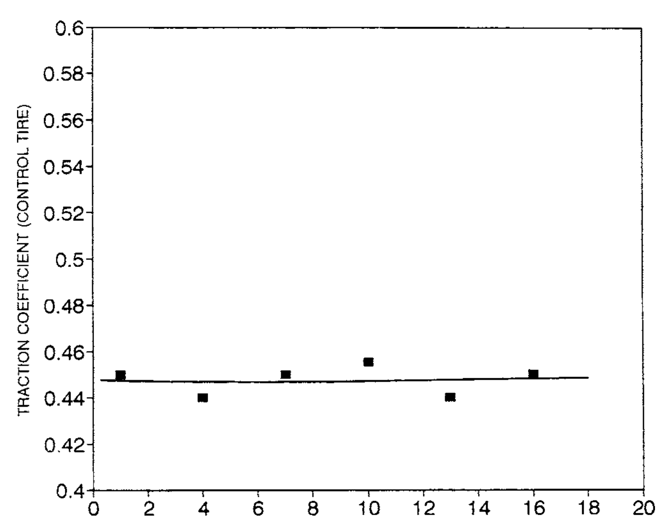

FIG. A1.1 Typical Control Tire Data With No Significant Trend, With Good Test Precision, That is, Small Standard Error of Estimate, *SCV* = 1.5 %, *R(calc)* = 0.04

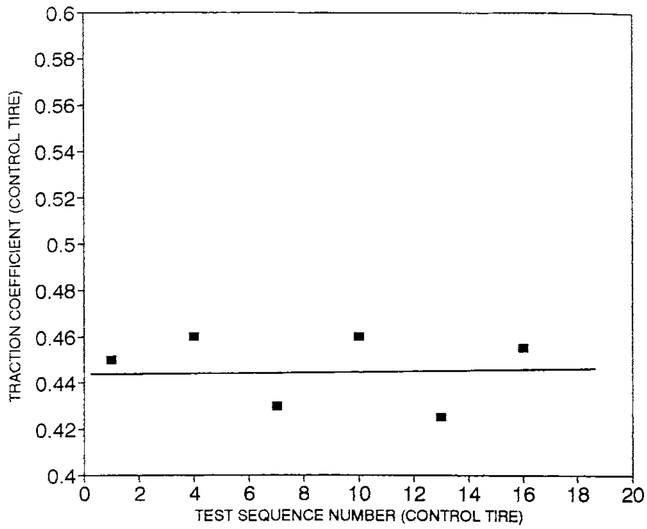

FIG. A1.2 Typical Control Tire Data With No Significant Trend, With Poorer Test Precision, *SCV* = 3.8 %, *R(calc)* = 0.17

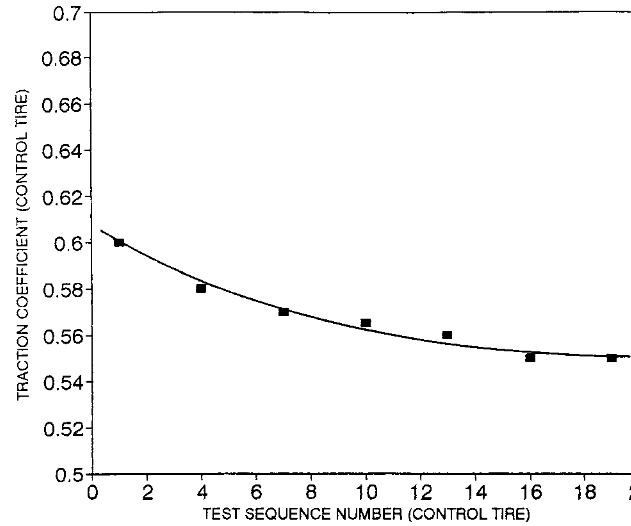

FIG. A1.4 Typical Control Tire Data With a Significant Non-Linear Trend

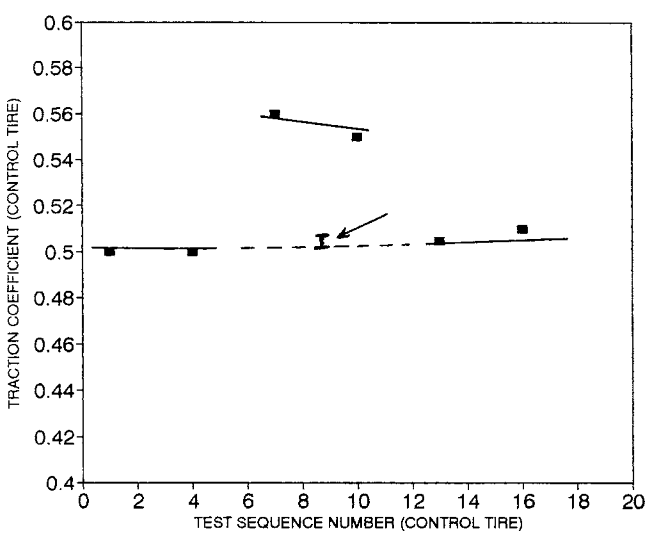

FIG. A1.3 Typical Control Tire Data With a Significant Transient or Step Response, With [4 SE(MR)] "Error Bar" Indicated by Arrow

and regression analysis; this is designated as the main regression or MR level. The SE calculated from the regression analysis, when multiplied by four (see 8.4 and especially 8.4.4.1) gives a value for [4 SE(MR)] as indicated by the error bar in Fig. A1.3. No transformation was applied to the data for Fig. A1.3.

A1.1.3 Fig. A1.4 illustrates a very typical curvilinear downward trend in control set data. Such a trend is normally due to test pavement polishing (reduction in microtexture) due to the traction testing. Fig. A1.5 is a plot of the transformed data of Fig. A1.4, that is, log (test sequence number) versus log (traction coefficient). It illustrates a good linear relationship and permits a linear regression analysis to be conducted on the log transformed data. The very significant $R_{(calc)}$ value is 0.987 and SE (on CV basis) is 1.1 %.

A1.2 *Correction Calculation Example: Method A*—Table A1.1 lists control set and candidate set wet traction coefficient data for a test program with nineteen data sets. Test Plan A was used with two candidate tire sets between successive control set tests. Table A1.2 lists the control set wet traction coefficients for C1 through C7. These data are the same as the data shown in Fig. A1.4 and Fig. A1.5 and represent a significant curvilinear trend.

A1.2.1 Table A1.3 lists the data as given in Table A1.1 along with columns that are needed for the correction based on non-weighted calculations. The corrected traction coefficients for T1 through T12 are given in the fourth column along with the correction factors as used and the values for F1 through F6. The last two columns give the as-measured TPI and the corrected TPI. The reference standard tire is T1.

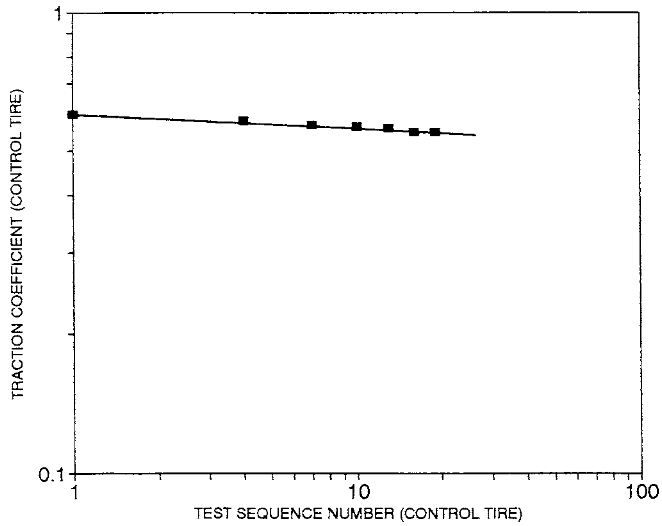

FIG. A1.5 Transformed Data of Fig. A1.4 (Log-Log Linear Plot), *SCV* = 1.1 %, *R(calc)* = 0.987

TABLE A1.1 Control and Candidate Set Traction Coefficient Data

Test Sequence Number	Set Identification	Wet Traction Coefficient
1	C1	0.60
2	T1	0.61
3	T2	0.65
4	C2	0.58
5	T3	0.70
6	T4	0.66
7	C3	0.57
8	T5	0.64
9	T6	0.58
10	C4	0.57
11	T7	0.59
12	T8	0.57
13	C5	0.56
14	T9	0.65
15	T10	0.63
16	C6	0.55
17	T11	0.69
18	T12	0.56
19	C7	0.55

TABLE A1.2 Control Set Traction Data

C1	0.60
C2	0.58
C3	0.57
C4	0.57
C5	0.56
C6	0.55
C7	0.55

TABLE A1.3 Correction Calculations for Wet Traction Example[A]

Test Sequence Number	Set ID	As-Measured Coefficient	Corrected Coefficient	F-Factor Used	F-Factor Value	As-Measured TPI	Corrected TPI
1	C1	0.60	...	...	...	...	...
2	T1	0.61	0.620	F1	0.983	100	100
3	T2	0.65	0.661	F1	0.983	107	107
4	C2	0.58	...	...	...	...	...
5	T3	0.70	0.730	F2	0.958	115	118
6	T4	0.66	0.689	F2	0.958	108	111
7	C3	0.57	...	...	...	...	...
8	T5	0.64	0.677	F3	0.946	105	109
9	T6	0.58	0.613	F3	0.946	95	99
10	C4	0.57	...	...	...	...	...
11	T7	0.59	0.629	F4	0.938	97	101
12	T8	0.57	0.608	F4	0.938	93	98
13	C5	0.56	...	...	...	...	...
14	T9	0.65	0.703	F5	0.925	107	113
15	T10	0.63	0.681	F5	0.925	103	110
16	C6	0.55	...	...	...	...	...
17	T11	0.69	0.753	F6	0.917	113	121
18	T12	0.56	0.611	F6	0.917	92	98
19	C7	0.55	...	...	...	...	...

[A]Corrected parameter value = measured parameter value/Fj.

A2. RECOMMENDED WEIGHTING PROCEDURE FOR CORRECTION FACTORS

A2.1 The test plans as given in 7.3 are reproduced here as Table A2.1. In any significant trend situation between successive Ci values, the magnitude of the trend differs for the Ti values contained within the two C values. If the trend is substantial and if the highest degree of correction is sought, a weighting procedure may be applied. This weighting is especially important for Plan B.

A2.2 *Weighting Procedure: Plan A*—Since there are three units (of time or testing sequence) between successive C values, the weighting is based on a two-thirds and one-third weight for the respective Ti values according to Table A2.2. The table applies to Method A. For Method B replace the C1 value with C_{avg}. A linear trend is assumed between the two successive Ci values.

A2.2.1 The calculation is continued in accordance with the format given in Table A2.2 in groups of two from beginning to end, for all candidate tires, T1 through Ti. The correction of the measured parameter is conducted in accordance with 8.5.1 or 9.3.1.

TABLE A2.1 Test Plans

Plan A:	
	Test in the order: C1, T1, T2, C2, T3, T4, C3, T5, T6, C4, etc.
Plan B:	
	Test in the order: C1, T1, T2, T3, C2, T4, T5, T6, C3, T7, T8, T9, C4, etc.

TABLE A2.2 Correction Factors for Plan A (Method A)[A]

Ti Value	Correction Factor
T1	F1(T1)A = [⅔ (C1) + ⅓ (C2)]/C1
T2	F1(T2)A = [⅓ (C1) + ⅔ (C2)]/C1
T3	F2(T3)A = [⅔ (C2) + ⅓ (C3)]/C1
T4	F2(T4)A = [⅓ (C2) + ⅔ (C3)]/C1
etc.	

[A]Fi(Ti)A = correction factor, for Group i, for Ti, for Plan A (*i* = 1,2,3, etc.).

A2.3 *Weighting Procedure: Plan B*—In Plan B there are four units (time or testing sequence) between successive C values and the weighting is based on a¼, ½, ¾ basis as given in Table A2.3. The table applies to Method A. For Method B replace the C1 value with C_{avg}. A linear trend is assumed between the two successive Ci values.

A2.3.1 The calculation is continued in accordance with the format as given in Table A2.3 in groups of three from beginning to end, for all candidate tires, T1 through Ti. The correction of the measured parameter is conducted in accordance with 8.5.1 or 9.3.1.

TABLE A2.3 Correction Factors for Plan B (Method A)[A]

Ti Value	Correction Factor
T1	F1(T1)B = [¾ (C1) + ¼ (C2)]/C1
T2	F1(T2)B = [½ (C1) + ½ (C2)]/C1
T3	F1(T3)B = [¼ (C1) + ¾ (C2)]/C1
T4	F2(T4)B = [¾ (C2) + ¼ (C3)]/C1
T5	F2(T5)B = [½ (C2) + ½ (C3)]/C1
T6	F2(T6)B = [¼ (C2) + ¾ (C3)]/C1
etc.	

[A]Fi(Ti)B = correction factor, Group i, for Ti, Plan B.

APPENDIXES

(Nonmandatory Information)

X1. STATISTICAL MODEL FOR TRACTION MEASUREMENT

X1.1 General Model Development and Background

X1.1.1 For any established traction measurement system, each traction measurement μ(i) can be represented as a linear additive combination of fixed or bias terms and random terms as indicated by Eq X1.1. The equation contains typical representative terms for wet traction testing; other terms may be needed in addition to or as a replacement for these terms. The equation applies to any brief or narrow time period of testing.

$$\mu(i) = bo + b(tire) + b(tx) + \varepsilon(loc) + \varepsilon(dw) + \varepsilon(vel) + \varepsilon(eqp) + \varepsilon(op) \quad (X1.1)$$

where:

μ(i) = a traction measurement made at time (i), that is, in a short time interval or window,
bo = a constant or fixed value term characteristic of a particular test method or system; it is also characteristic of selected test parameter values not enumerated below, for example, target speed, type of test vehicle, etc.,
b(tire) = a fixed term characteristic of the tire or tire set under test,
b(tx) = a fixed term characteristic of a particular pavement and its condition at the particular test sequence time period in question,
ε*(loc)* = a random value term [normal distribution, (+ , –) values, mean = 0], due to variations in location on the test surface,
ε*(dw)* = a similar random value term, due to variations in water depth,
ε*(vel)* = a similar random value term, due to variations in actual test speed,
ε*(eqp)* = a similar random value term, due to variations in equipment operation, and
ε*(op)* = a similar random value term, due to variations in operator technique.

X1.1.2 Any individual traction measurement μ (*i*) is equal to the summed value of all terms on the right hand side of the equation. The usual testing technique of replication (averages of several runs) for μ(*i*) measurements during a narrow time period, that is, at time (*i*), reduces the influence of the random "ε" terms. The average of each ε value approaches zero (sum of + and – values) and the sum of all "ε" terms approaches zero, as the number of values averaged increases. In the limit, with a very large number of measurements, the sum of all "ε" terms equals zero.

X1.2 Application of Model to Variation in Pavement (Other) Conditions

X1.2.1 Changes in test conditions, either trend variations or transient shift variations, are systematic changes that occur over a long time period and are represented for each test period by a particular value for the fixed term *b(tx)*. When a sufficient number of replications have been made, in test time period (*i*), the sum of all "ε" terms is small compared to the magnitude of the measured avg μ(*i*). Under these conditions the avg μ(*i*) is a function of the combined value of all three fixed or "*b*" terms. When replicated sets of control tire measurements are made at regularly spaced intervals over a long time span, the values of each set avg μ(*i*) are influenced by the changing value of the *b(tx)* term as indicated by Eq X1.2.

$$avg\ \mu(i) - [bo + b(tire)] = b(tx)(i) \quad (X1.2)$$

where:

avg μ(i) = average value obtained in short time (i), after a given time or test interval, and
b(tx)(i) = term characteristic of pavement (or other conditions, or both) at that particular interval or period.

X1.2.2 Since the same test system is used and a standard or control tire is used, the bracket sum is a constant. Variations inμ (*i*) reflect variations in *b(tx)*, the term that is a function of the texture and any other characteristic of the test that changes with time or use period of the pavement.

X1.2.3 Thus well replicated control tire testing forμ (*i*) measurement over a series of regularly spaced time or test sequence intervals, can be used to obtain an indication of the changes in the texture or other characteristic conditions of a pavement (or test system, or both) that vary with pavement use (or time, or both).

X2. PROPAGATION OF ERROR (VARIATION) IN TIRE TRACTION PERFORMANCE EVALUATION

X2.1 Background

X2.1.1 Without test error, tire traction performance could be evaluated by review of the as measured (absolute) traction coefficients or other parameters. Test run replication and correction for time trends or other perturbations would not be needed. However, when measured traction parameters that have a certain random or systematic variation are used in mathematical calculations that express tire performance, the form of the mathematical relationship is important in determining the variation of the calculated performance parameters. The statistical technique that addresses this topic is called "Propagation of Error." See footnote 5 for background on the calculation algorithms as given in Appendix X2. The propagation of error expressions are given in terms of random variations or errors.[3]

X2.1.2 The purpose of Appendix X2 is to show that the act of applying corrections to measured traction coefficients and the TPI values derived therefrom, does influence the variance or the ± random variation limits on the resulting TPI values.

X2.1.3 For any general functional relationship of the form as given by Eq X2.1:

$$Y = \varphi(x1, x2, \ldots) \quad (X2.1)$$

the variance of *Y, Var(Y)*, is given by Eq X2.2 in terms of the partial differential of the function with respect to $x1$ times the variance of $x1$, *Var(x1)* plus the partial differential of the function with respect to $x2$ times the variance of $x2$, *Var(x2)*, etc.:

$$Var(Y) = [\partial\varphi(x1, x2, \ldots)/\partial x1]^2 Var(x1) \quad (X2.2)$$

$$+[\partial\varphi(x1, x2, \ldots)/\partial x2]^2 Var(x2) + \ldots$$

With simple linear relationships for the function, the differentials become constants and the equation for *Var(Y)* becomes:

$$Var(Y) = k1[Var(x1)] + k2[Var(x2)] \quad (X2.3)$$

For the simplest linear form, a sum or difference relationship given by Eq X2.4:

$$Y = x1 \pm x2 \quad (X2.4)$$

the *Var(Y)* is given by Eq X2.5 since the differentials in Eq X2.2 are unity:

$$Var(Y) = Var(x1) + Var(x2) \quad (X2.5)$$

Thus the act of adding or subtracting two measured values, each having a variance associated with its measurement, substantially increases the variance of the sum or difference. If both $x1$ and $x2$ have the same variance, the variance of the sum or difference is two times the individual variances.

X2.1.4 With any functional form beyond a sum or difference, the variance of Y is influenced by the value for the differentials. For a ratio or quotient, as given by Eq X2.6,

$$Y = x1/x2 \quad (X2.6)$$

the variance of Y is given by Eq X2.7 and the evaluation of *Var(Y)* has to be made at some selected values for $x1$ and $x2$.

$$Var(Y) = (x1/x2)^2 [\{Var(x1)/(x1)^2\} + \{Var(x2)/(x2)^2\}] \quad (X2.7)$$

X2.2 Basis for Calculating the Variance of TPI

X2.2.1 Since the evaluation of traction performance is normally conducted using the Traction Performance Index, or TPI, the variance of this parameter is of direct importance. The influence of traction measurement variations on the variance of TPI can best be illustrated by using a typical data set as given in Table X2.1. The Fj corrections as given in Table X2.1 are in accordance with Method A, without any weighting.

X2.2.2 In the succeeding sections, TPI variance evaluations are conducted for two cases: (*1*) no corrections and (*2*) with trend or shift corrections, or both. This will be done on the basis of the simple ratio with the factor of 100 ignored, that is, for the term TPI/100, see Eq 5 in the main body of this practice. At the end of each illustrative set of calculations the factor is applied to give the standard deviation in terms of actual TPI units.

X2.2.3 Testing experience shows that a typical value for single pass (or test) traction coefficient standard deviation in braking trailer wet traction testing is 0.020. This value may be different for certain other testing but it is sufficient for Appendix X2 and the relative comparisons that will be made. This corresponds to a variance of 0.00040. When averages of four tests are to be used for TPI calculation, the variance of averages of four is one fourth of the variance of single pass measurements, or 0.00010. The average of four variance, that is, 0.0001, will be used for both examples as given in X3.3 through X3.5. It is assumed that this value applies to all measured traction coefficients, that is, to T1 through T4 and C1 through C3.

X2.3 Variance for TPI: Case 1—No Trend/Shift Corrections

X2.3.1 For both cases (that is, no corrections and corrections) only the first four sequence numbers in Table X2.1 will be used for the calculations. This simplifies the numerical

TABLE X2.1 Typical Wet Traction Data Set

NOTE 1—Each measured μ value is the average of four passes or tests runs at some selected speed and surface.

Test Sequence Number	Set ID	Measured μ	Corrected μ	Fj	As Measured TPI	Corrected TPI
1	C1	0.60	...	...	...	...
2	T1	0.61	0.621	0.983	100	100
3	T2	0.65	0.661	0.983	107	107
4	C2	0.58	...	...	...	...
5	T3	0.70	0.731	0.958	115	118
6	T4	0.66	0.689	0.958	108	111
7	C3	0.57	...	...	...	...

[3] Ku, H. H., "Precision Measurement and Calibration—Statistical Concepts and Procedures," *Special Publication 300*, Vol. 1, NIST, 1969, pp. 331–341.

evaluations. Data are shown in the table for seven sequence numbers to show that a continued trend exists for the Ci values. The variance of the TPI values may be calculated from the Measured μ values for the first four test sequence numbers when a value is given for the traction measurement standard deviation. Only T1 and T2 (traction coefficients) are of importance for this no trend calculation.

X2.3.1.1 Table X2.1 shows that although the Measured μ values are different from the Corrected μ values, the TPI values are not different (to the nearest whole index number) when comparing the "as measured" TPI to the Corrected TPI. This equivalence of TPI values is due to the fact that the reference standard T (or T1) lies within the C values used. Subsequent TPI values do show a difference between the" as measured" and the corrected values as the Ci values trend downward.

X2.3.2 The variance for TPI, which is given by Eq X2.8, is based on the "measured" values for T1 and T2 in Table X2.1 and on the basis of T1 being the reference standard (ref std) as defined in Eq 1. Since the variance has to be evaluated at a specific point or value of Ti, an average value, *avg T*, is used for the evaluations. Evaluating Eq X2.8 with numerical values gives Eq X2.9:

$$Var(\mathrm{TPI}) = (avg\ T/T1)^2\left[(Var(T)/(avg\ T)^2) + (Var(T)/(ref\ T)^2)\right] \quad (X2.8)$$

where:

avg T = average of as measured T1 and T2 (see Table X2.1),
ref T = as measured T1 (see Table X2.1), and
Var (T) = 0.00010.

and with numerical substitution:

$$Var(\mathrm{TPI}) = (0.63/0.61)^2\left[(0.0001/(0.63)^2) + (0.0001/(0.61)^2)\right]$$

$$Var(\mathrm{TPI}) = 0.00055 \text{ or standard deviation } (\mathrm{TPI}) = 0.0235 \quad (X2.9)$$

X2.3.3 When the factor of 100 is applied to the TPI ratio, the result is 2.35 = 2.4 units or points as the standard deviation of TPI. This gives on a ±2 standard deviation basis, the value of ±4.8. Thus on repeated testing of the first four sequences (each sequence number being the average of four passes) for T1 and T2, the TPI for T2 would be expected to fall within a range of ±4.8 TPI points about the value of 107 as given in Table X2.1, that is, from 102 to 112, when 4.8 is rounded to 5.0.

X2.4 Variance for TPI: Case 2—Trend Corrections

X2.4.1 When corrections are made, the relevant equations used to calculate a corrected TPI are Eq X2.10-X2.12. Eq X2.12 is expressed in the format where higher measured parameters (traction coefficients) indicate superior performance. Only the first four sequence numbers will be used. In these equations, C1, C2, candidate Ti and reference standard Ti are measured traction coefficients. The variance of TPI is given in terms of Var(*F*1) and Var(μ(c)Ti) (see X2.4.2 and X2.4.3):

$$F1 = (\mathrm{C1} + \mathrm{C2})/2\mathrm{C1} \quad (X2.10)$$

$$\mu(c)Ti = \text{Measured } \mu(Ti)/(F1) \quad (X2.11)$$

$$\text{Corrected TPI} = \left[\mu(c)Ti/\mu(c) \text{ reference standard}\right]100 \quad (X2.12)$$

X2.4.2 The variance for *F*1 is given by Eq X2.13, which, upon evaluation, gives Eq X2.14. The variance of C1 + C2 is equal to two times the variance of C1 and the variance of 2C1 is 2^2 times the variance of C1.

$$Var(F1) = (C1 + C2/2C1)^2\left[\{2Var/(C1)/(C1+C2)^2\} + \{Var(2\ C\ 1)/(2\ C\ 1)^2\}\right] \quad (X2.13)$$

and with numerical substitution:

$$Var(F1) = (1.18/1.20)^2\left[\{0.0002/(1.18)^2\} + \{0.0004/(1.20)^2\}\right]$$

$$Var(F1) = 0.000408 \text{ or standard deviation } (F1) = 0.0202 \quad (X2.14)$$

X2.4.3 The next step is to evaluate the variance for the corrected traction coefficients, Var(μ(c)Ti), in terms of the Measured μ, designated as μ(m), and F1. The variance is evaluated for the average μ(m), designated as $\bar{\mu}$(m), that is, the average of 0.61 and 0.65 for T1 and T2, respectively. This variance, designated as Var(μ(c)Ti), is given by Eq X2.15 using the average measured traction coefficient, $\bar{\mu}$(m), and the evaluation is given by Eq X2.16:

$$Var(\mu(c)Ti) = (\bar{\mu}(m)/F1)^2\left(\{Var[\mu(m)]/[\bar{\mu}(m)]^2\} + \{Var/(F1)/(F2)^2\}\right) \quad (X2.15)$$

and with numerical substitution:

$$Var(\mu(c)Ti) = (0.63/0.983)^2\left(\{0.0001/[0.63]^2\} + \{0.000408/(0.983)^2\}\right)$$

$$Var(\mu(c)Ti) = 0.00028 \text{ or standard deviation } \mu(c)Ti = 0.0166 \quad (X2.16)$$

X2.4.4 The variance expression for the corrected TPI is given by Eq X2.17 and its evaluation is given by Eq X2.18 using the corrected orμ (c)Ti values (see column 4 of Table X2.1). The μ(c) for T1 and T2 is 0.641 and the corrected ref T value (or T1) is 0.621:

$$Var(\mathrm{Corr\ TPI}) = [\mu(c)Ti/\mu(c)ref\,T]^2\left(\{Var(\mu(c)Ti)/[\mu(c)Ti]^2\} + \{Var(\mu\ (c)\ r\,e\,f\ \ T)/[(\mu\ (c)\ r\,e\,f\ \ T)]^2\}\right) \quad (X2.17)$$

and with numerical substitution:

$$Var(\mathrm{Corr\ TPI}) = [0.641/0.621]^2\left(\{0.00028/[0.641]^2\} + \{0.00028/[0.621]^2\}\right)$$

$$Var(\mathrm{Corr\ TPI}) = 0.00122 \text{ or standard deviation} = 0.0349 \quad (X2.18)$$

X2.4.5 When the factor of 100 is applied to the TPI ratio, the result is 3.49 units or points as the standard deviation of Corrected TPI. This gives on a ±2 standard deviation basis, the value of ±7.0. Thus on repeated testing of the first four sequences (each sequence number being the average of four passes) for C1, T1, T2, and C2, the Corrected TPI for T2 would be expected to fall within a range of ±7.0 TPI points about the value of 107 as given in Table X2.1, that is, from 100 to 113.

X2.5 Comparing the Variation of TPI—No Correction Versus Correction

X2.5.1 The calculations as outlined in the preceding sections may be compared by use of Table X2.2 for the two cases. The results of Table X2.2 are confined to random variations or errors.

X2.5.2 The table shows that when corrections are applied, the random variations in measuring F1 and μ(c)Ti inflate the value of the TPI variance and its derived parameters, the standard deviation and the ±2 standard deviation limits, compared to the no correction case. The TPI variance for the corrected case is 2.2 times the variance for no correction. The reasons for this are outlined clearly in X3.1. In this particular situation although the same value is obtained for the "no correction" TPI as for the Corrected TPI for T2 as stated in X3.3.1.1, the limits on the equivalent TPI values are higher for the corrected case.

TABLE X2.2 Comparison of Variation on TPI: No Correction Versus Correction

Correction	TPI Variance	TPI Standard Deviation	±2 Standard Deviation Range on TPI (min – max)
No	0.00055	0.0235	102 to 112 (10)
Yes	0.00122	0.0349	100 to 113 (13)

X2.5.3 The justification for corrections is the presence of systematic variation (trends or shifts, or both) in operating conditions over the entire operating period of any program. When these trends or shifts are significant or large, or both, the improved accuracy of the candidate TPI values that correction produces substantially outweighs the inflated TPI variance due to random fluctuations. The corrections offset the perturbations due to trends or shifts and yield an improved (more accurate) comparison among the candidate tires evaluated. Increased replication will reduce the random variation and the ± limits for the case where corrections are applied. As Appendix X1 clearly shows, increased replication will not eliminate the influence of the systematic trends or shifts.

X2.5.4 However, when trends or shifts are not significant over any evaluation period, the use of the control data to make arbitrary corrections on the measured traction coefficients will inflate the limits on TPI and reduce the sensitivity to detect significant differences among the candidate TPI values. This loss of sensitivity applies to both Methods A and B of this practice.