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INVESTIGATION OF THE VALIDITY OF THE ASTM STANDARD FOR COMPUTATION OF INTERNATIONAL FRICTION INDEX

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
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DEDICATION

I dedicate this work to my mother Kokila, my grandmother Subbamma, my brother Srikanth and my friend Issaac Kommineni. Without their constant support and encouragement I would never have achieved this. To my friends Meeta, Ramya, Qing, and Vishwanthi for their constant support, help and friendship.

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INVESTIGATION OF THE VALIDITY OF THE ASTM STANDARD FOR COMPUTATION OF INTERNATIONAL FRICTION INDEX

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ABSTRACT

Runway friction testing is performed in order to enhance the safety of aircraft operation on runways. Preventative maintenance friction surveys are performed to determine if there is any deterioration of the frictional resistance on the surface over a period of time and to determine if there is a need for corrective maintenance. In addition operational performance friction surveys are performed to determine frictional properties of a pavement surface in order to provide corrective action information in maintaining safe take-off or landing performance limits. A major issue encountered in both types of friction evaluation on runways is the standardization of the friction measurements from different Continuous Friction Measuring Equipment (CFME). The International Friction Index (IFI) has been formulated to address the above issue and determine the friction condition of a given runway is a standardized format. The ASTM recommended standard procedure to compute the IFI of a runway surface employs two distinct parameters to express the IFI; F60 is the friction value adjusted to a slip speed of 60 km/h and correlated to the standard Dynamic Friction Tester (DFT) measurement. And Sp is the speed constant which is governed by the mean profile depth of that surface.

The primary objective of this thesis is to investigate the reliability of the current ASTM procedure to standardize runway friction measurements in terms of IFI. Based on the ASTM standard procedure, two equipment specific calibration constants (A and B) are assigned for each CFME during calibration. Then, in subsequent testing those

calibrations constants can be used to adjust the equipment measurements to reliable IFI values. Just as much as A and B are presumed to be characteristic of any given CFME, they are also expected to be independent of the operational speed. The main objective of the annual NASA Runway Friction Workshop held in Wallops Island, Virginia, is to calibrate commonly used CFMEs such that all calibrated equipment would provide a standard reading (i.e. IFI) on a particular surface.

During validation of the existing ASTM procedure using the NASA Runway Friction Workshop data it was observed that the single value-based IFI predictions of the calibrated CFMEs were inaccurate resulting in low correlations with DFT measured values. Therefore, a landing pilot should not be left to make a safe decision with such an uncertain single standard friction value because the actual standard friction value could very well be much less than this value. Hence a modified procedure was formulated to treat the calibration constants A and B as normally distributed random variables even for the same CFME. The new procedure can be used to predict the IFI (F60) of a given runway surface within a desired confidence interval. Since the modified procedure predicts a range of IFI for a given runway surface within two bounds, a landing pilot's decision would be made easier based on his/her experience on critical IFI values. However, even the validation of the modified procedure presented some difficulties since the DFT measurements on a few validated surfaces plotted completely outside the range of F60 predicted by the modified method.

Furthermore, although the ASTM standard stipulates the IFI (F60) predictions to be independent of the testing speed, data from the NASA Runway Friction Workshop indicates a significant difference in the predictions from the two testing speeds of 65 km/hr and 95 km/hr, with the results from the 65 km/hr tests yielding better correlations with the corresponding DFT measurements. The above anomaly could be attributed to the significantly different FR60 values obtained when the 65 km/hr data (FR65) and 95 km/hr data (FR95) are adjusted to a slip speed of 60 km/hr. Extended analytical investigations revealed that the expected testing speed independency of the FR60 for a particular CFME cannot be supported by the ASTM defined general linear relationship between Sp and the mean profile depth which probably has been formulated to satisfy a multitude of CFMEs operating on a number of selected test surfaces. This very reason can also be attributed to the above mentioned outliers observed during the validation of the modified procedure.

CHAPTER ONE

INTRODUCTION

Airport runway friction testing is performed to evaluate the coefficient of friction (μ) on runways and it is categorized into two distinct operations. Federal Aviation Administration (FAA) refers them to as maintenance procedures and operational procedures. Airport runway friction testing is performed in order to evaluate the condition of the runway surface for operational and maintenance purposes. This enhances the safety of operations on the runways.

(a) Preventative maintenance friction surveys are performed to determine if there is any deterioration of the frictional resistance on the surface over a period of time and to determine if there is a need for corrective maintenance. Table 1 shows the threshold friction values of airport runway surfaces with respect to different measuring devices. Meanwhile Table 2 illustrates the information specific to the Grip tester.

(b) Operational performance friction surveys are performed to determine frictional properties of a pavement surface in order to provide corrective action information in maintaining safe take-off or landing performance limits.

Table 1 ICAO Recommendations of μ Values for Preventative Maintenance of Runway

	Design Target		Intervention Level		Minimum Level	
Speed (km/hr)	65	95	65	95	65	95
MuMeter	0.72	0.66	0.52	0.38	0.42	0.26
BV-11	0.82	0.74	0.60	0.47	0.50	0.34
SFT	0.82	0.74	0.60	0.47	0.50	0.34
RFT	0.82	0.74	0.60	0.54	0.50	0.41
Tatra	0.76	0.67	0.57	0.52	0.48	0.42
GripTester	0.74	0.64	0.53	0.36	0.43	0.24

Table 2 ICAO Recommendations for μ Values and IFI for the Grip Tester

	Target Levels for New Surfaces	Maintenance Planning Levels	Minimum Allowable Friction Levels
μ(65 km/hr)	0.74	0.53	0.43
μ(95 km/hr)	0.64	0.36	0.24
Sp min (km/hr)	31.0	11.6	7.7
MTD min (mm)	0.375	0.205	0.170
F60 min	0.232	0.119	0.114

1.1. NASA Wallops Runway Friction Workshop

NASA Wallops Tire/Runway Friction Workshop is conducted annually at the NASA base in Wallops Island, Virginia to compare the measurements of each friction testing device. During NASA Tire/Friction Workshops, friction data has been collected using ground vehicles on a number of textured test surfaces. These tests have been performed by various device manufacturers and end users with a focus on preventative maintenance friction. The main aim of comparison of friction data is to establish a basic correlation, if any does exist among different friction devices. Also the results of the above Friction Workshop can indicate various issues within the testing procedures used and the data collected can be used to better understand the performance and evaluation of each friction measuring equipment. In this thesis the data from past three years of NASA Wallops Tire/Runway Friction Workshop has been analyzed and the calibration constants for each equipment used at the Friction Workshop have been computed using the relevant ASTM standard methodology [1].

Data collected on the same runway pavement surface generally confirms that there are differences among friction measuring devices because each device reports considerably different friction values on the same surface. It is reported that they also show inconsistent repeatability within themselves and no direct correlation to aircraft wheel braking performance. Therefore, standardization of measurements from different equipment is essential. During 1993 – 1998, the data for the computation of International Friction Index (IFI) at the test sites of Wallops Flight Facility was based on the combination of MTD (volumetric texture depth using glass beads) and the BPN (British Pendulum Number). Based on the ASTM standards [1] Dynamic Friction Tester (DFT) is considered to be the master device for friction measurement in NASA Wallops Runway Friction Workshop, and DFT at 20 km/hr has been used for standardization instead of BPN.

1.2. Objectives of NASA Wallops Tire/Friction Workshop

The following are the primary objectives of the above workshop

(a) To obtain better understanding of different runway friction measurement procedures and factors influencing tire/runway friction performance.

(b) Expand the existing friction measurement vehicle correlations to include new devices.

(c) Provide opportunity to observe new test and pavement treatment equipment in operation.

(d) Evaluate different pavement roughness measuring devices.

(e) Identify methods to improve harmonization between different measurement devices and test procedures used throughout the world.

1.3. International Friction Index

The main aim of PIARC experiment [1] is to harmonize the wet friction and texture measurements which produce the International Friction Index. Similarly the goal of the Joint Winter Runway Friction Measurement Program (JWRFMP) [2] is to harmonize the friction measurements which are obtained from different ground test vehicles on a wide range of winter runway conditions [2]. There are three types of friction measuring systems in general; fixed slip, side force and locked wheel. It is observed that macro-texture parameter is required in order to harmonize the results. Therefore it is clear that a friction index is represented by two numbers. One of them is related to macro-texture measurement and the other is related to a friction measurement. The main aim of all these systems is to predict the same values for these macro-texture and friction number on a given pavement.

1.4. ASTM Designation E 1960: Standard Practice for Calculating the International Friction Index (IFI)

This practice covers the calculation of the IFI from a measurement of pavement macro-texture and wet pavement friction. The IFI was developed in the PIARC international experiment [1] to compare and harmonize texture and skid resistance measurements. This index allows for the harmonizing of friction measurements with different equipment to a common calibrated index. The above ASTM practice provides for harmonization of friction reported for devices that use a smooth tread test tire.

(a) The IFI consists of two parameters; the calibrated wet friction at 60 km/hr (F60) and the speed constant of wet pavement friction (Sp).

(b) The mean profile depth (MPD) and mean texture depth (MTD) have been shown to be useful in predicting the speed constant (gradient) of wet pavement friction.

(c) A linear transformation of the estimated friction at 60 km/hr provides the calibrated F60 value. The estimated friction at 60 km/hr is determined from a measurement made at any speed by using the speed constant.

1.4.1. Summary of Practice

This practice uses measured data of the pavement surface on macro-texture, and measured friction (FRS) on wet pavement.

The practice accommodates the above data measured with different equipment at any measuring speed. The following steps are followed in obtaining the above.

(a) Measurement of the pavement macro-texture is used to estimate the speed constant (Sp) by using Equation (1)

$$Sp = 14.2 + 89.7 \times MPD \tag{1}$$

where MPD is the Mean Profile Depth which can be obtained from the Circular Texture Meter (CT Meter).

(b) Determination of F60 using the DFT value at 20 km/hr in accordance with test method E1911 [1] for each of the test sections is given by using Equation (2)

$$F60 = 0.081 + 0.732 \times DFT20 \times e^{\left(-\frac{40}{Sp}\right)} \tag{2}$$

(c) Calculation of Friction at 60 km/hr (FR60) with the measured friction (FRS) at some slip speed (S) and the speed constant of the pavement (Sp) using Equation(3)

$$FR60 = FRS \times e^{\left(\frac{(S-60)}{Sp}\right)} \tag{3}$$

(d) Linear regression of FR60 (Equation (3)) and F60 (Equation (2)) is used in Equation (4) to obtain the calibration constants A and B.

$$F60 = A + B \times FR60 \tag{4}$$

(e) Reporting of F60 and Sp as IFI (F60, Sp)

1.4.2. Significance and Use of ASTM Standard Methodology

(a) This is the practice for calculating the IFI of the pavement. The IFI has proven useful for harmonization of the friction measuring equipment. F60 and Sp have proven to be able to predict the speed dependence of wet pavement-related measurements of various types of friction measuring equipment. The two IFI parameters (F60 and Sp in Section 1.4.1) have been found to be reliable predictors of the dependence of wet pavement friction on tire slip and vehicle speed.

(b) The IFI parameters F60 and Sp can be used to calculate the calibrated friction at another slip speed using the following transformation equation.

$$FS = F60 * e^{\left(\frac{(60-S)}{Sp}\right)} \tag{5}$$

(c) The IFI model given in Equation (6) describes the relationship between the values of wet pavement friction FRS measured at a slip speed of S and the friction values measured by different types of equipment(i=1to n)

For the ith equipment,

$$F60 = A_i + B_i * FRS_i * e^{\left(\frac{-(60-Si)}{(a+b*TX)}\right)} \tag{6}$$

(d) The significance of the IFI model is that the measurement of friction with a device does not have to be at one particular speed used in the experiment. FRS can be measured at one slip speed S and is always adjusted to 60 km/hr (FR60). Thus if a device cannot maintain its normal operating speed and must run at some higher or lower speed because of traffic, the model still works well. In that case S is determined by the vehicle speed (V) which can be converted to S by multiplying V by the percent slip for fixed slip equipment or by multiplying V by the sine of the slip angle for side force equipment.

1.5. Objectives of Proposed Research

The research program described in this thesis seeks to study the limitations of the ASTM IFI computational procedure and verify its effectiveness in the standardization of friction measurements from different CFMEs. In order to achieve this objective, first a comprehensive analysis is performed on the friction data obtained from four years of NASA Wallops Tire/Friction Workshops. Then, an alternative procedures for expressing the calibration constants A and B is explored. Finally, the applicability of the standard Speed Constant (Sp) and the Mean Texture Depth (MPD) relationship is also investigated.

1.6. Thesis Organization

This thesis is divided into five chapters. The first chapter is the Introduction where the background of the friction measurements and their standardization is introduced. The second chapter consists of the analysis of NASA Runway Friction Workshop data using the existing methodology. The third chapter describes the validation of data using the current method of data analysis. Data Analysis with the modified method is presented in the fourth chapter while the final chapter describes the conclusions reached based on the research findings.

CHAPTER TWO

ANALYSIS OF NASA RUNWAY FRICTION WORKSHOP DATA

2.1. Calibration of the NASA GT

At NASA Runway Friction Workshop all the friction evaluation equipment are operated at two different speeds; 65 and 95 km/hr. Two kinds of equipment are used in general i.e. Dynamic Friction Tester and Continuous Friction Measuring Equipment (CFME). CFMEs are operated in repeated runs on a given surface in order to obtain data with an improved accuracy. After the data collection the outlying data are removed and the average value of all the runs is computed as the friction value on a given surface at a particular speed.

With known DFT_{20} and MPD values from NASA Wallops Friction Workshop data, Sp is calculated using Equation (1) while F60 is calculated using Equation (2). In some years both Sp and F60 values for the tested sections are provided. The friction data obtained at 65 km/hr and 95 km/hr are termed FR65 and FR95 respectively. By substituting FR65 and Sp in Equation (3) one can obtain FR60 for any equipment (ex: NASA GT) when it is operated at 65 km/hr. Similarly from FR95 and Sp one can obtain FR60 for that equipment at 95 km/hr. Then using FR60 obtained from two different speeds and DFT F60 in Equation (4) two sets of values for A and B are obtained for the same equipment.
Table 3 and Table 4 show that the calibration constants A and B obtained from Equation (4) by considering data from individual runs is not significantly different from those obtained from the average friction values for both speeds of 65 and 95 km/hr.

Table 3 A and B Values Obtained by Using Data from Individual Runs and Average Friction Values for NASA GT at 65 km/hr

Friction Data	From Individual Runs			From Average Friction Values		
DFT	VT	JAPAN	PTI	VT	JAPAN	PTI
B	0.554828	0.534307	0.570466	0.561565	0.542445	0.57852
A	0.172741	0.183946	0.171466	0.170984	0.181703	0.169304

Table 4 A and B Values Obtained by Using Data from Individual Runs and Average Friction Values for NASA GT at 95 km/hr

Friction Data	From Individual Runs			From Average Friction Values		
DFT	VT	JAPAN	PTI	VT	JAPAN	PTI
B	0.532811	0.491654	0.537819	0.543063	0.50548	0.549053
A	0.217433	0.232943	0.218977	0.212714	0.227517	0.213653

Regression analysis is performed to evaluate the goodness of fit as seen in Figures 1, 2 and 3 for NASA GT at 65 km/hr and 4, 5 and 6 for NASA GT at 95 km/hr with three DFTs.

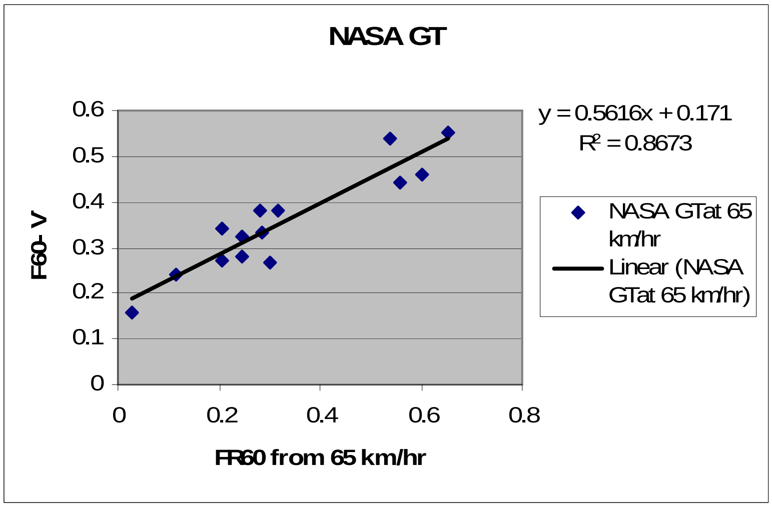

Figure 1 NASA GT May 2007 Calibration Constants from F60 and FR60 at 65 km/hr with DFT-VT

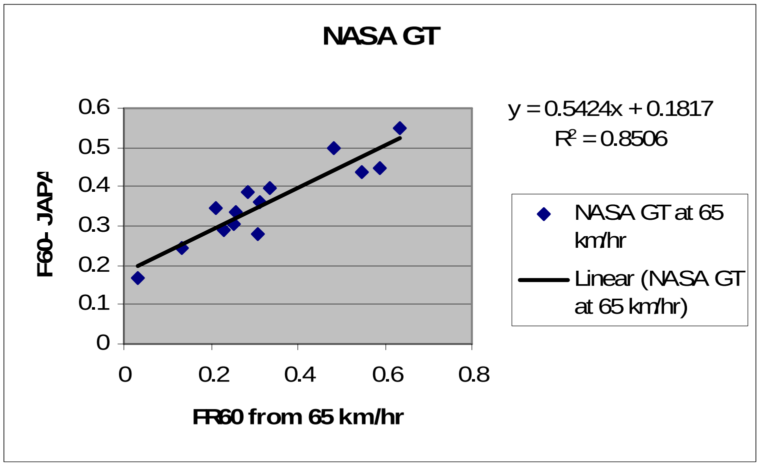

Figure 2 NASA GT May 2007 Calibration Constants from F60 and FR60 at 65 km/hr with DFT-Japan

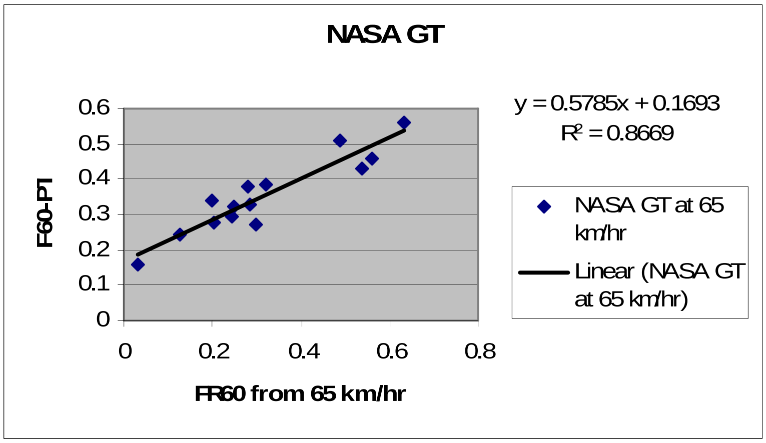

Figure 3 NASA GT May 2007 Calibration Constants from F60 and FR60 at 65 km/hr with DFT-PTI

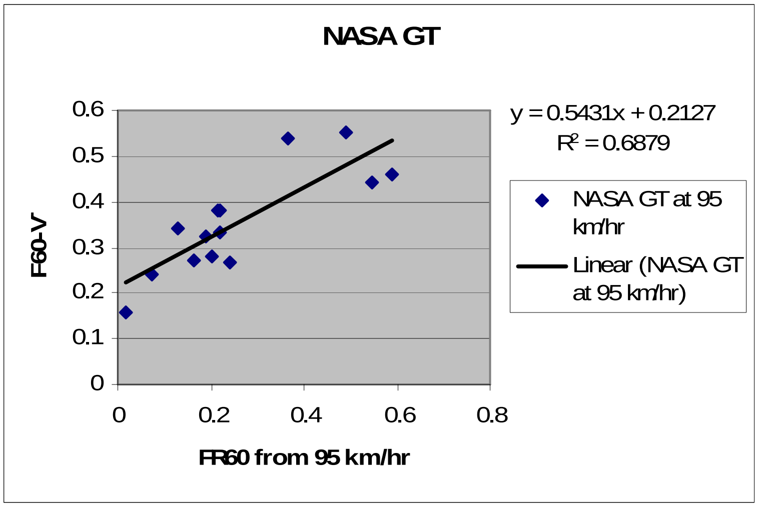

Figure 4 NASA GT May 2007 Calibration Constants from F60 and FR60 at 95 km/hr with DFT-VT

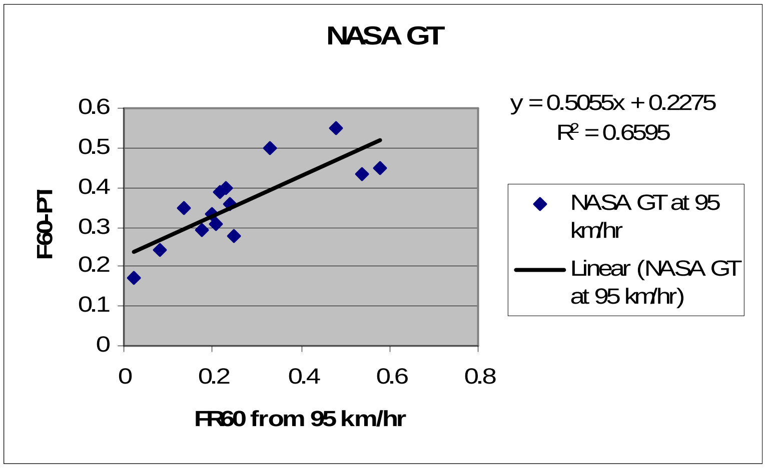

Figure 5 NASA GT May 2007 Calibration Constants from F60 and FR60 at 95 km/hr with DFT-JAPAN

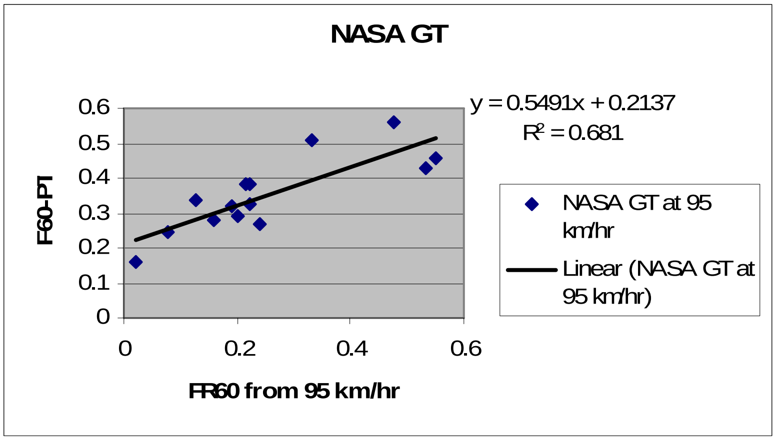

Figure 6 NASA GT May 2007 Calibration Constants from F60 and FR60 at 95 km/hr with DFT-PTI

For the year 2007, the values of A, B and R^2 for the year 2007 are shown in Table 5

Table 5 The Variation of Calibration Constants A and B for NASA GT at 65 and 95 km/hr

Speed	65 km/hr			95 km/hr		
DFT	VT	JAPAN	PTI	VT	JAPAN	PTI
A	0.171	0.1817	0.1693	0.2127	0.2275	0.2137
B	0.5616	0.5424	0.5785	0.5431	0.5055	0.5491
R^2	0.8673	0.8506	0.8669	0.6879	0.6595	0.681

Similarly the calibration constants for the FAA RFT are shown in the Appendix A

2.1.1. Determination of the Effect of Operating Speed on the Calibration

ASTM standard stipulates that the calibration constants A and B must be equipment constants independent of operating speed. In order to achieve this condition the equipment measurements (FRS) are adjusted to a slip speed of 60 km/hr (Equation 3). Therefore the t-test was performed to check whether FR60 values from FR65 and FR95 are significantly different from each other. The results of t-test are shown in Table 6 for all the three DFTs: VT, JAPAN and PTI.

The t-test for paired differences between two sample for means:

Null Hypothesis (H0): $\mu_d=0$

Alternative Hypothesis (Ha): $\mu_d\neq0$

Table 6 t-test results for Comparison of NASA GT FR60 from 65 km/hr and 95 km/hr with Three DFT-VT, Japan & PTI

FR60 (From 65 km/hr vs. from 95 km/hr)			
DFT	VT	Japan	PTI
t_0	4.87	5.37	5.08
Degrees of Freedom	13	13	13
LOC	90%	90%	90%
t-Critical	1.35	1.35	1.35

It can be seen from Table 6 that t_o> t-critical, the null hypothesis is rejected at a 90 % L.O.C. Therefore FR60 obtained from FR65 and FR95 are significantly different from each other at a 90% Level of Confidence.

2.2. Calibration for Averaged Operating Speeds

In general the equipment is operated at two different speeds i.e. 65 km/hr and 95 km/hr. It was observed that the FR60 values obtained at 65 km/hr and 95 km/hr differed significantly. Therefore, by averaging these two FR60s a single value of FR60 can be obtained. Furthermore, by using this average FR60 and DFT F60 in Equation (4) one can obtain a single correlation for A and B as opposed to different correlations for each operating speed. This averaging is done in order to obtain single values for A and B based on the logic that A and B are constants for any given equipment.

Figures 7, 8 and 9 show the regression analysis for the linear relationship between $F60$ and average FR60. The calibration constants for the averaged FR60 for three years (2005, 2006, and 2007) are shown in Table 7.

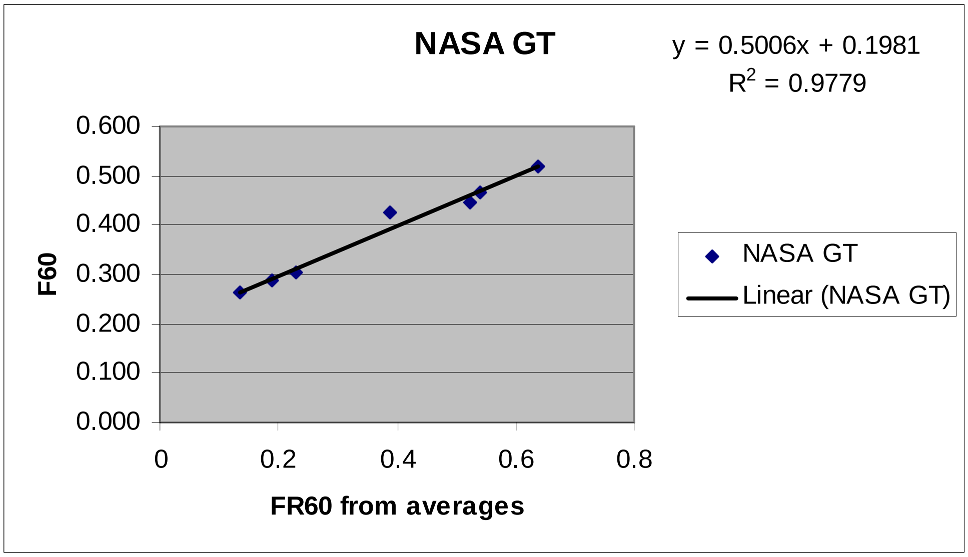

Figure 7 NASA GT May 2005 Average Calibration Constants

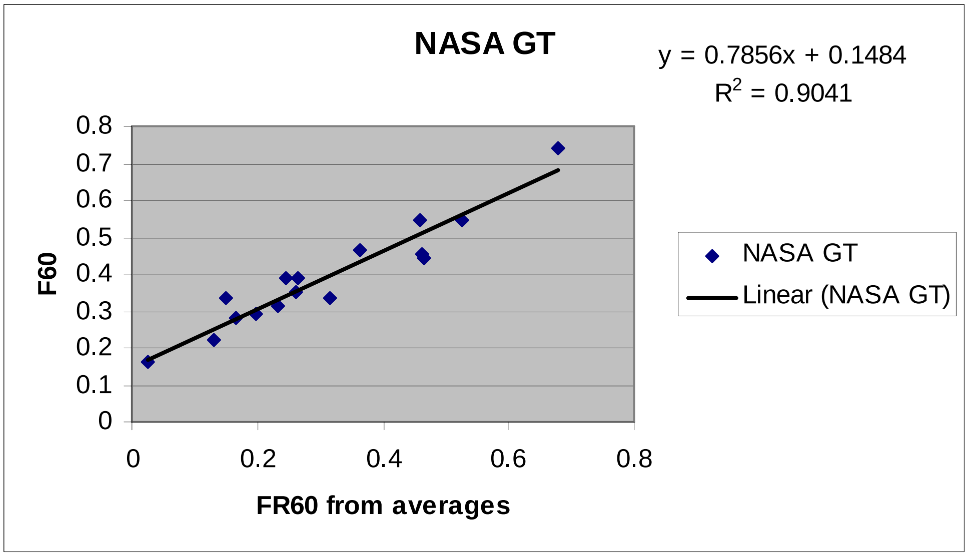

Figure 8 NASA GT May 2006 Average Calibration Constants

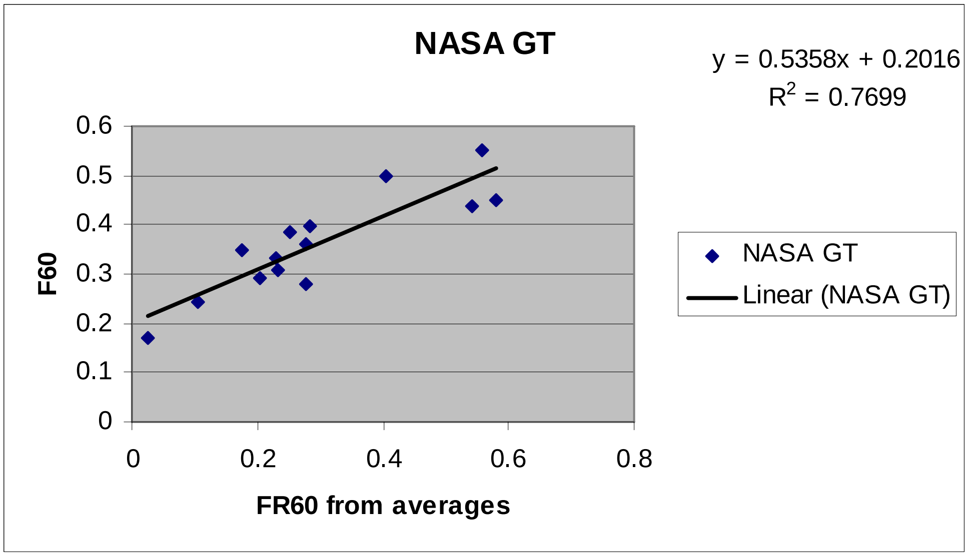

Figure 9 NASA GT May 2007 Average Calibration Constants

Table 7 NASA GT Average Calibration Constants

Equipment	NASAGT		
Year	2005	2006	2007
A	0.198	0.148	0.202
B	0.500	0.786	0.536
R^2	0.978	0.904	0.769

CHAPTER THREE

VALIDATION FOR THE CURRENT METHOD OF DATA ANALYSIS

3.1. Validation for Individual Operating Speeds

During the calibration operation A and B values are computed for all the friction measuring equipment at their characteristic operating speeds. A and B values obtained for these friction measuring equipment can then be used for future testing. Therefore a validation procedure was performed in this thesis to validate the calibrated A and B values by predicting the measurements on the other four test surfaces. In this exercise the data obtained from 2007 NASA Wallops Runway Friction Workshop is used for the purpose of validation. Of the fourteen surfaces included in the entire testing program the data for the following ten test surfaces is used for computing A and B.

Calibration surface set: A, B, C, D, E, F, G, Echo 1, EK 1, EK 2

Thus the data on the following four test surfaces are used for the purpose of validating the computed A and B.

Validation surface set: R4, Echo 2, EK 3, and EK 4

At NASA Wallops Runway Friction Workshop all the equipment are operated at 65 km/hr and 95 km/hr. As shown in Section 2.2 when A and B values are calculated for these two speeds for any given equipment their values were found to be different. However per ASTM standards [1] A and B values are expected to be constants for a given equipment. For each operating speed (65 km/hr and 95 km/hr), F60 for the validation surfaces were predicted using A and B values obtained on the calibration set of surfaces using three different DFT and CT meters; VT, JAPAN and PTI and FR60 obtained from the validation surfaces (Equation (3)). Therefore F60 computed for validation test surfaces using Equation (2) are compared with those predicted above. The results are shown in Figures 10, 11 and 12 for a speed of 65 km/hr and Figures 13, 14 and 15 for a speed of 95 km/hr.

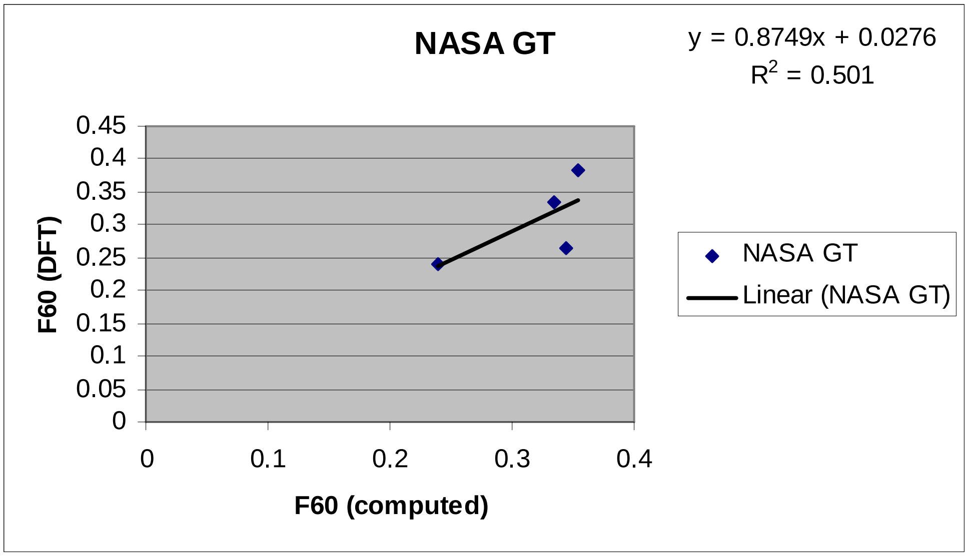

Figure 10 DFT F60 for Validation Set vs. F60 from Calibration Set, May 2007 (VT Instruments- CT meter and DFT)

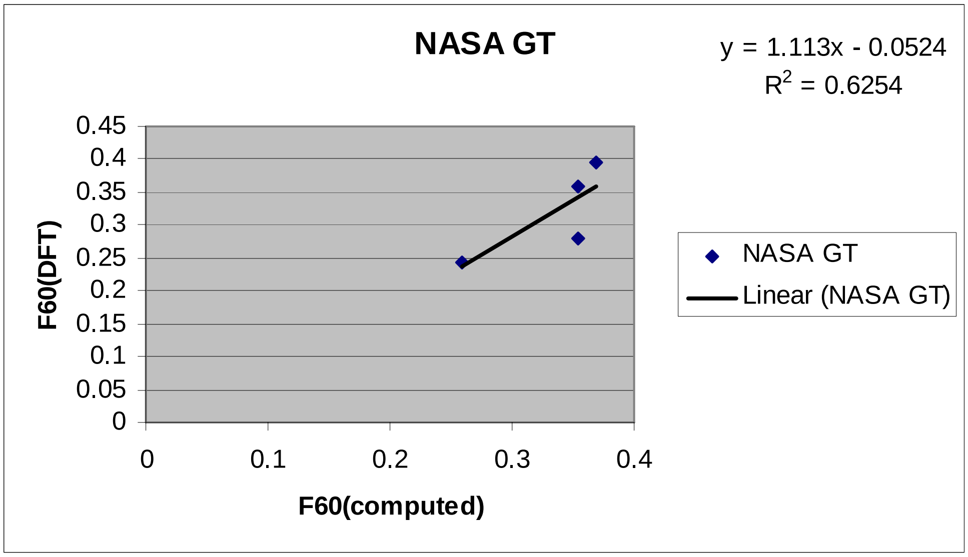

Figure 11 DFT F60 for Validation Set vs. F60 from Calibration Set, May 2007 (Japan Instruments- CT Meter and DFT)

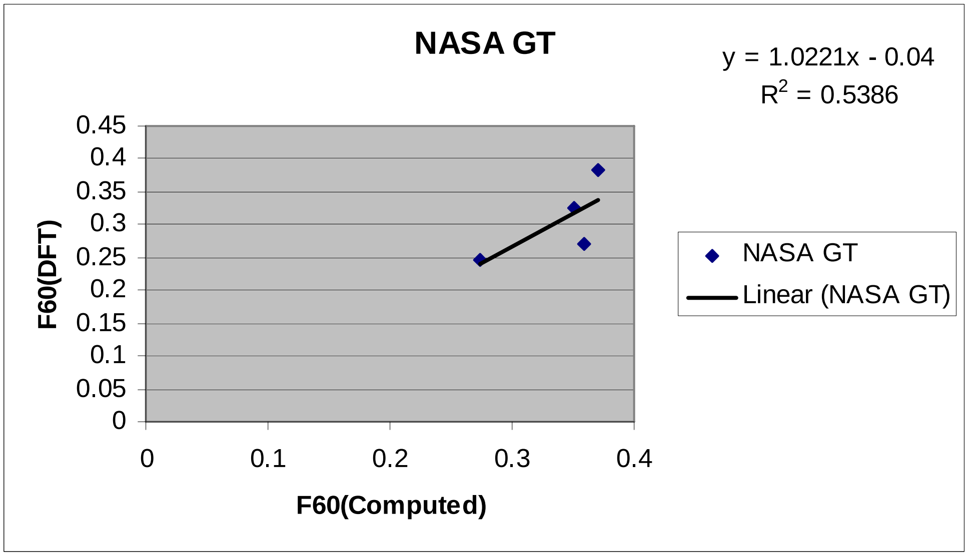

Figure 12 DFT F60 for Validation Set vs. F60 from Calibration Set, May 2007 (PTI Instruments- CT Meter and DFT)

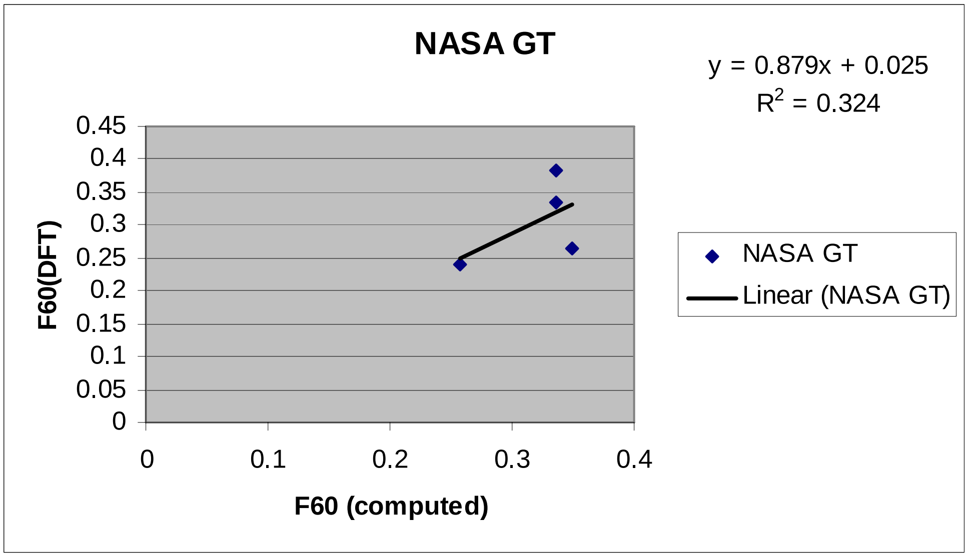

Figure 13 DFT F60 for Validation Set vs. F60 from Calibration Set, May 2007 (VT Instruments- CT Meter and DFT)

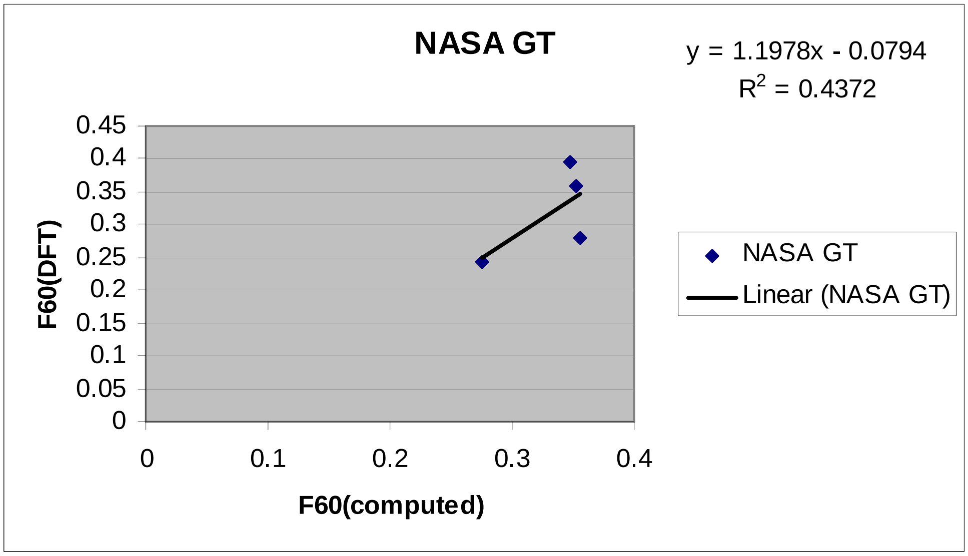

Figure 14 DFT F60 for Validation Set vs. F60 from Calibration Set, May 2007 (JAPAN Instruments- CT Meter and DFT)

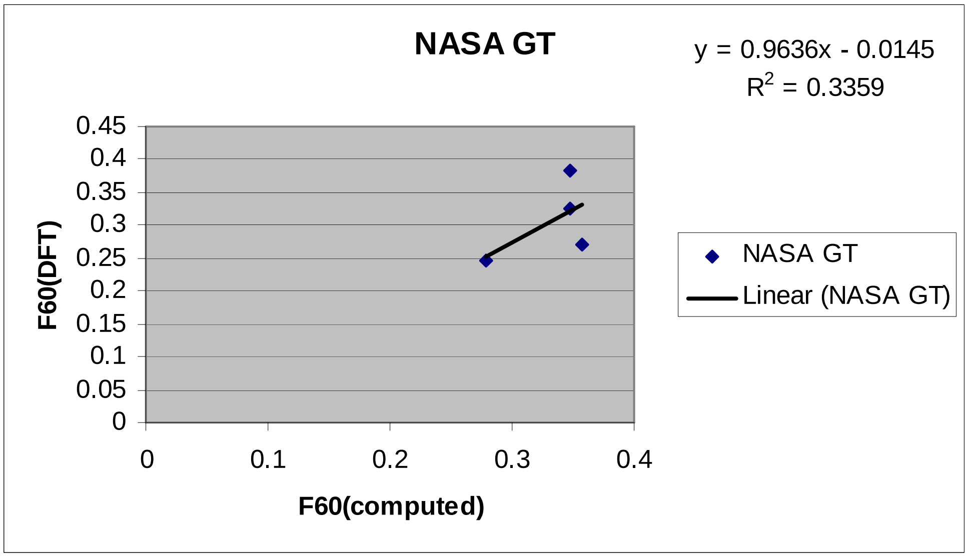

Figure 15 DFT F60 for Validation Set vs. F60 from Calibration Set, May 2007 (PTI Instruments- CT Meter and DFT)

Table 8 shows the correlation results between DFT F60 and computed F60 at different speeds.

Table 8 Correlation between Computed F60 and DFT F60

NASA Grip Tester						
DFT	VT		JAPAN		PTI	
Operating Speed	65 km/hr	95 km/hr	65 km/hr	95 km/hr	65 km/hr	95 km/hr
Correlation between F60 (DFT) and F60(Computed)	0.501	0.324	0.625	0.437	0.538	0.335

Similarly correlation for FAA RFT is given in the Appendix A.

CHAPTER FOUR

DATA ANALYSIS WITH THE MODIFIED METHOD

4.1. Calibration with Modified Method

At NASA Wallops Tire/Friction Workshop 14 test surfaces are provided for the purpose of runway friction testing. The main purpose of the testing program is to measure friction on the test surfaces and adjust those measurements to the International Friction Index IFI (F60, Sp). Various types of equipment are used for the purpose of friction testing of which the Dynamic Friction Tester (DFT) is treated as the standard device which measures IFI on the test surface. All other equipment are Continuous Friction Measuring Equipment (CFME) which acquire dynamic measurements. CFMEs are operated at the two speeds of 65 km/hr and 95 km/hr. ASTM standard Equation (3) is used to adjust the measured friction value FRS at a given slip speed 'S' to a common slip speed of 60 km/hr. The current ASTM procedure calculates the calibration constants from the regression of the adjusted measurement (FR60) and F60 obtained from the Dynamic Friction Tester (DFT) on the same test surface. Two single value calibration constants (A and B) are obtained for each CFME with respect to DFT. The calibration constants vary from equipment to equipment while they are presumed to be constants for particular equipment. The above procedure is illustrated for the NASA Grip Tester in Chapter 3. The application of the ASTM procedure is in that when the calibrated CFME is operated on a new test surface the friction value obtained on that new surface is converted to FR60 using Equation (3). FR60 is then adjusted to F60 using the above calibration constants. Therefore the predicted friction value i.e. IFI on the new test surface is a single constant value which could differ from the actual IFI on the new test surface by a certain margin of error.

The validation procedure described in Chapter 3 assumes that only ten (10) surfaces are used for testing to obtain the calibration constants while the remaining four (4) surfaces are provided for validation. The predicted F60 values for the four surfaces are then correlated with the F60 obtained from the DFT on the same test surfaces. The results of the above correlation for NASA GT are shown in Table 8 and Figures 6 to 11 in Chapter 3. The validation results indicate that by using single values of A and B one can obtain a single value for F60 which can deviate in either direction from the actual friction value on that surface. In order to address this problem an alternative procedure is developed to standardize the runway friction measurements. In this procedure the calibration constants A and B are treated as random variables instead of single valued variables. The predicted F60 will then be a random variable which would be within a certain confidence interval.

4.1.1. Procedure for Randomization of the Calibration Constants

The ASTM standard practice for calibration of friction testers recommends the use of at least 10 surfaces to compute the calibration constants. Therefore from the 14 available test surfaces, a sample size of 13 surfaces is used for calibration with 1 surface left out for validation in each trial. The reason for selecting 13 surfaces is to compute A and B with a better accuracy by employing more of the available data. In each of such 14 trials the surface left out itself can be made the validation test surface. Therefore using this technique, 14 different validations can be performed. Since there are 13 surfaces for calibration and every time 10 surfaces are used to compute the calibration constants, ${}^{13}C_{10}$ combinations are available to compute two ranges for A and B. The minimum, maximum and mean of A, B for all the possible 14 trials are shown in Table 9 , 10 for 65 km/hr and 95 km/hr with DFT-VT, Table 11, 12 for 65 km/hr and 95 km/hr with DFT-Japan and Table 13 and 14 for 65 km/hr and 95 km/hr with DFT-PTI.

Table 9 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 65 km/hr with DFT-VT

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	0.1460	0.2132	0.1748	0.0129	0.4181	0.6939	0.5551	0.0378
B	0.1329	0.2050	0.1666	0.0123	0.4372	0.7300	0.5866	0.0432
C	0.1329	0.2037	0.1638	0.0115	0.4423	0.7300	0.5972	0.0392
D	0.1464	0.2129	0.1754	0.0125	0.4225	0.6980	0.5553	0.0374
E	0.1329	0.1938	0.1618	0.0105	0.4568	0.7169	0.5772	0.0346
F	0.1533	0.2140	0.1780	0.0121	0.4129	0.6235	0.5239	0.0349
G	0.1329	0.2140	0.1742	0.0145	0.4129	0.7300	0.5488	0.0532
Echo1	0.1403	0.1992	0.1658	0.0112	0.4381	0.6915	0.5660	0.0355
EK1	0.1462	0.2140	0.1822	0.0137	0.4129	0.6888	0.5358	0.0411
EK2	0.1419	0.2042	0.1695	0.0122	0.4353	0.6999	0.5634	0.0365
R4	0.1441	0.2136	0.1787	0.0120	0.4310	0.7300	0.5567	0.0385
Echo2	0.1422	0.2030	0.1686	0.0116	0.4295	0.6916	0.5614	0.0361
EK3	0.1431	0.2054	0.1710	0.0121	0.4327	0.7010	0.5612	0.0365
EK4	0.1365	0.2140	0.1706	0.0141	0.4129	0.7167	0.5626	0.0403

Table 10 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 95 km/hr with DFT-VT

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	0.1522	0.2724	0.2168	0.0199	0.3548	0.8990	0.5414	0.0843
B	0.1334	0.2439	0.1983	0.0238	0.3738	0.9906	0.6310	0.1235
C	0.1334	0.2448	0.1945	0.0223	0.3687	0.9906	0.6481	0.1163
D	0.1536	0.2700	0.2168	0.0195	0.3604	0.9185	0.5439	0.0846
E	0.1334	0.2458	0.2013	0.0187	0.3946	0.9630	0.5735	0.0853
F	0.1582	0.2553	0.2120	0.0170	0.3414	0.7886	0.5106	0.0733
G	0.1334	0.2669	0.2181	0.0206	0.3414	0.9906	0.5047	0.0994
Echo1	0.1438	0.2494	0.2062	0.0180	0.3772	0.8945	0.5571	0.0814
EK1	0.1518	0.2724	0.2303	0.0192	0.3414	0.8735	0.5013	0.0846
EK2	0.1472	0.2598	0.2110	0.0192	0.3705	0.9078	0.5519	0.0833
R4	0.1467	0.2724	0.2189	0.0195	0.3655	0.9906	0.5477	0.0885
Echo2	0.1439	0.2490	0.2061	0.0180	0.3771	0.8928	0.5570	0.0812
EK3	0.1490	0.2594	0.2116	0.0189	0.3696	0.9159	0.5510	0.0834
EK4	0.1375	0.2724	0.2145	0.0223	0.3414	0.9502	0.5443	0.0910

Table 11 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 65 km/hr with DFT-Japan

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	0.1526	0.2335	0.1854	0.0143	0.3938	0.6856	0.5362	0.0422
B	0.1398	0.2171	0.1761	0.0135	0.4191	0.7253	0.5723	0.0476
C	0.1398	0.2141	0.1727	0.0122	0.4303	0.7253	0.5849	0.0418
D	0.1518	0.2296	0.1845	0.0139	0.4000	0.6895	0.5382	0.0416
E	0.1398	0.2079	0.1730	0.0115	0.4314	0.7090	0.5578	0.0381
F	0.1563	0.2370	0.1863	0.0136	0.3649	0.6406	0.5156	0.0423
G	0.1398	0.2370	0.1883	0.0162	0.3649	0.7253	0.5171	0.0559
Echo1	0.1462	0.2124	0.1765	0.0121	0.4147	0.6810	0.5473	0.0388
EK1	0.1530	0.2370	0.1958	0.0154	0.3649	0.6796	0.5094	0.0466
EK2	0.1492	0.2213	0.1808	0.0133	0.4088	0.6900	0.5434	0.0404
R4	0.1491	0.2355	0.1893	0.0137	0.4035	0.7253	0.5373	0.0435
Echo2	0.1505	0.2179	0.1802	0.0127	0.4008	0.6804	0.5404	0.0400
EK3	0.1497	0.2206	0.1816	0.0130	0.4063	0.6920	0.5417	0.0404
EK4	0.1486	0.2370	0.1858	0.0161	0.3649	0.6932	0.5339	0.0460

Table 12 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 95 km/hr with DFT-Japan

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	0.1608	0.2962	0.2310	0.0219	0.2912	0.8582	0.5052	0.0900
B	0.1459	0.2737	0.2119	0.0262	0.3453	0.9533	0.5978	0.1307
C	0.1459	0.2717	0.2079	0.0246	0.3450	0.9533	0.6155	0.1229
D	0.1608	0.2918	0.2300	0.0214	0.3028	0.8740	0.5086	0.0899
E	0.1459	0.2730	0.2168	0.0210	0.3393	0.9235	0.5352	0.0912
F	0.1628	0.2780	0.2246	0.0189	0.2907	0.8031	0.4900	0.0820
G	0.1459	0.2942	0.2348	0.0223	0.2907	0.9533	0.4574	0.0992
Echo1	0.1528	0.2741	0.2211	0.0199	0.3313	0.8579	0.5198	0.0864
EK1	0.1613	0.2962	0.2484	0.0211	0.2907	0.8425	0.4535	0.0898
EK2	0.1566	0.2849	0.2261	0.0211	0.3140	0.8639	0.5139	0.0887
R4	0.1576	0.2962	0.2332	0.0216	0.3040	0.9533	0.5106	0.0944
Echo2	0.1537	0.2737	0.2212	0.0197	0.3306	0.8538	0.5183	0.0860
EK3	0.1575	0.2815	0.2257	0.0206	0.3194	0.8728	0.5140	0.0885
EK4	0.1506	0.2962	0.2331	0.0246	0.2907	0.8816	0.4971	0.0968

Table 13 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 65 km/hr with DFT-PTI

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	0.1429	0.2131	0.1715	0.0130	0.4221	0.7044	0.5742	0.0400
B	0.1328	0.2021	0.1627	0.0113	0.4589	0.7440	0.6141	0.0399
C	0.1328	0.2120	0.1640	0.0122	0.4170	0.7440	0.6062	0.0453
D	0.1451	0.2127	0.1727	0.0125	0.4250	0.7065	0.5729	0.0394
E	0.1328	0.1955	0.1601	0.0102	0.4600	0.7277	0.5948	0.0361
F	0.1483	0.2176	0.1750	0.0127	0.4089	0.6488	0.5456	0.0413
G	0.1328	0.2176	0.1760	0.0146	0.4089	0.7440	0.5513	0.0541
Echo1	0.1377	0.2014	0.1646	0.0112	0.4384	0.6965	0.5819	0.0376
EK1	0.1449	0.2176	0.1814	0.0139	0.4089	0.6907	0.5490	0.0446
EK2	0.1412	0.2072	0.1689	0.0122	0.4342	0.7071	0.5784	0.0387
R4	0.1427	0.2150	0.1768	0.0120	0.4322	0.7440	0.5735	0.0406
Echo2	0.1414	0.2062	0.1680	0.0116	0.4277	0.6996	0.5764	0.0386
EK3	0.1436	0.2089	0.1708	0.0121	0.4319	0.7124	0.5762	0.0389
EK4	0.1373	0.2176	0.1697	0.0141	0.4089	0.7209	0.5775	0.0426

Table 14 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 95 km/hr with DFT-PTI

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	0.1493	0.2723	0.2165	0.0205	0.3471	0.8893	0.5488	0.0896
B	0.1367	0.2475	0.1965	0.0232	0.3857	0.9840	0.6533	0.1213
C	0.1367	0.2548	0.1979	0.0242	0.3411	0.9840	0.6426	0.1288
D	0.1514	0.2698	0.2168	0.0200	0.3548	0.9021	0.5505	0.0895
E	0.1367	0.2503	0.2026	0.0193	0.3884	0.9522	0.5796	0.0904
F	0.1542	0.2595	0.2117	0.0178	0.3316	0.8282	0.5253	0.0820
G	0.1377	0.2724	0.2219	0.0207	0.3316	0.9840	0.4938	0.0981
Echo1	0.1431	0.2533	0.2075	0.0185	0.3703	0.8937	0.5620	0.0862
EK1	0.1507	0.2724	0.2327	0.0197	0.3316	0.8818	0.5003	0.0902
EK2	0.1470	0.2634	0.2128	0.0198	0.3621	0.8940	0.5561	0.0884
R4	0.1495	0.2724	0.2195	0.0200	0.3589	0.9840	0.5537	0.0937
Echo2	0.1438	0.2536	0.2079	0.0185	0.3687	0.8918	0.5610	0.0862
EK3	0.1490	0.2638	0.2139	0.0195	0.3610	0.9065	0.5551	0.0889
EK4	0.1367	0.2724	0.2158	0.0229	0.3316	0.9277	0.5488	0.0963

4.2. Validation for the Proposed Method of Data Analysis

The NASA GT is operated on all of the 14 test surfaces at two different speeds of 65 km/hr and 95 km/hr from which FR60 values are obtained using Equation (3). As described in Section 4.1 since the calibration constants are obtained from ${}^{13}C_{10}$ combinations leaving out 1 surface in each trial, ${}^{13}C_{10}$ values of A and B are obtained. Then the left out surface becomes the validation surface in that iteration. F60 on the validation surface is then predicted using the ${}^{13}C_{10}$ values of A and B and FR60 obtained from each speed (Equation (4)). The above range of F60 values represent F60 as a random variable which is then compared with a single value of F60 measured on the validation test surface using the DFT. The predicted F60 can be compared with the DFT measured F60 on a given validation surface in two ways, as described in the Approaches 1 and 2.

Approach 1:

For all the 14 validation surfaces the mean of the predicted F60 can be correlated to the DFT F60 to verify the accuracy of validation. These results are shown in the Tables 15 and 16 for 65 km/hr and 95 km/hr respectively with DFT-VT, Tables 17 and 18 for 65 km/hr and 95 km/hr with DFT-Japan, Tables 19 and 20 for 65 km/hr and 95 km/hr with DFT-PTI. The correlation between the mean of predicted F60 and DFT F60 are shown in Figures 16-21 for 65 km/hr and 95 km/hr with DFT-VT, JAPAN, PTI DFTs.

In addition the t-test was performed to check whether the mean of the predicted F60 and the DFT measured F60 are significantly different from each other. The two hypotheses are:

H_0: Means of two samples are equal

H_a: Means of two samples are significantly different from each other

The results of the t-test are shown in Tables 21 and 22 for NASA GT and FAA RFT at 65 km/hr and 95 km/hr with three DFTs-VT, Japan and PTI. From these results it is seen that there is no evidence to reject the null hypothesis. Therefore it is concluded that there is no significant difference between the means of predicted F60 and the DFT F60.

Table 15 Mean of Predicted F60 and F60-VT Values for NASA GT at 65 km/hr

NASA GT at 65 km/hr, DFT-VT		
Surface	Mean of Predicted F60	F60-VT
A	0.290016	0.269372
B	0.492975	0.443917
C	0.522359	0.461858
D	0.311608	0.281669
E	0.279913	0.339642
F	0.460673	0.537889
G	0.532319	0.55103
Echo1	0.326049	0.379471
EK1	0.197704	0.158143
EK2	0.307802	0.322144
R4	0.3473	0.266002
Echo2	0.347425	0.38292
EK3	0.330054	0.333793
EK4	0.235554	0.239999

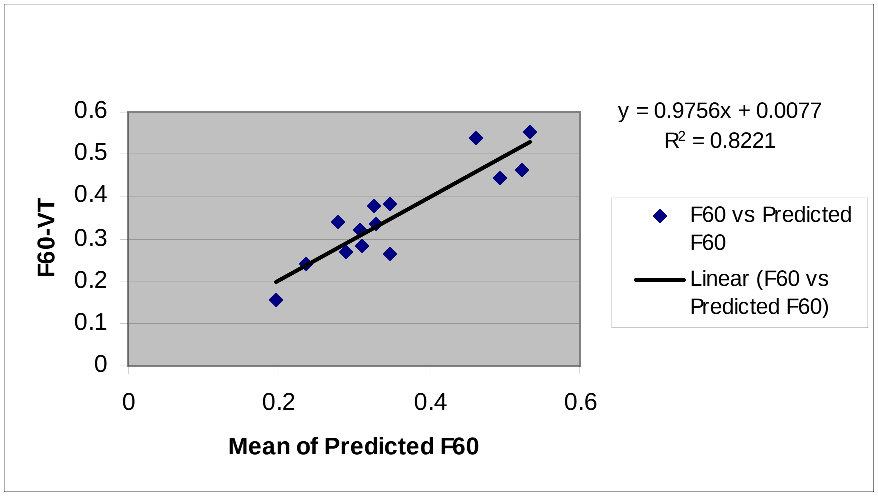

Figure 16 DFT F60 vs. Mean of Predicted F60 (NASA GT at 65 km/hr, DFT-VT)

Table 16 Mean of Predicted F60 and F60-VT Values for NASA GT at 95 km/hr

NASA GT at 95 km/hr, DFT-VT		
Surface	Mean of Predicted F60	F60-VT
A	0.305073	0.269372
B	0.543898	0.443917
C	0.576264	0.461858
D	0.326174	0.281669
E	0.275131	0.339642
F	0.3991	0.537889
G	0.465447	0.55103
Echo1	0.326364	0.379471
EK1	0.239679	0.158143
EK2	0.31612	0.322144
R4	0.351789	0.266002
Echo2	0.327531	0.38292
EK3	0.333225	0.333793
EK4	0.253561	0.239999

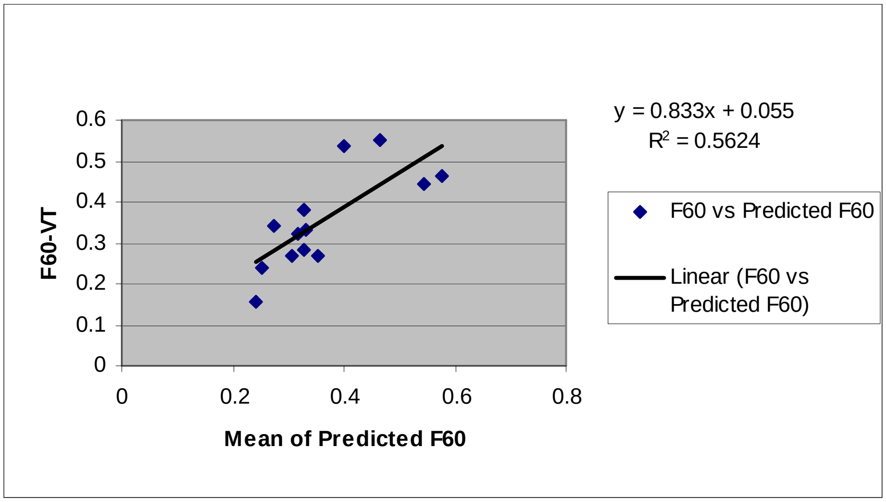

Figure 17 DFT F60 vs. Mean of Predicted F60 (NASA GT at 95 km/hr, DFT-VT)

Table 17 Mean of Predicted F60 and F60-Japan Values for NASA GT at 65 km/hr

NASA GT at 65 km/hr, DFT-Japan		
Surface	Mean of predicted F60	F60-Japan
A	0.307876	0.289988
B	0.488881	0.435573
C	0.515786	0.449775
D	0.321829	0.307021
E	0.292267	0.347154
F	0.434425	0.49739
G	0.516698	0.550702
Echo1	0.332894	0.386467
EK1	0.21237	0.169057
EK2	0.321707	0.333995
R4	0.355028	0.279373
Echo2	0.362604	0.396476
EK3	0.350163	0.360009
EK4	0.25601	0.243078

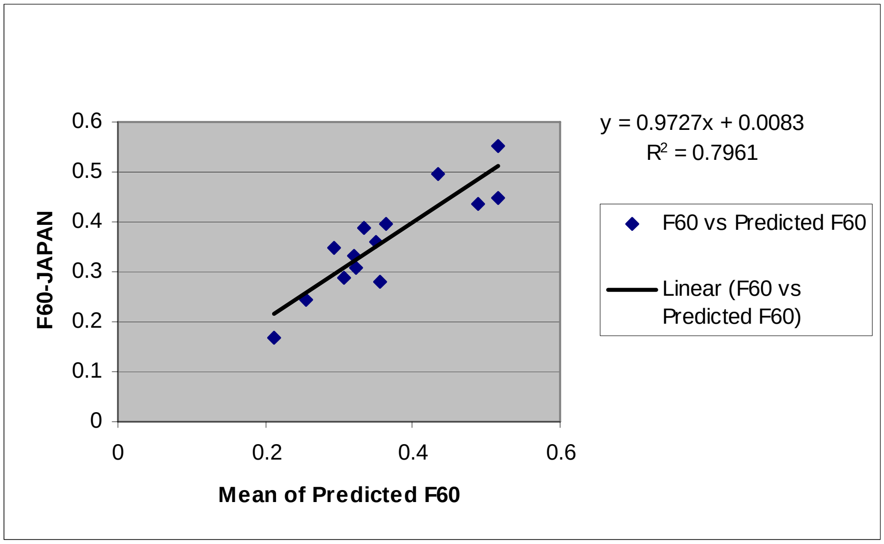

Figure 18 DFT F60 vs. Mean of Predicted F60 (NASA GT at 65 km/hr, DFT-Japan)

Table 18 Mean of Predicted F60 and F60-Japan Values for NASA GT at 95 km/hr

NASA GT at 95 km/hr, DFT-Japan		
Surface	Mean of Predicted F60	F60-Japan
A	0.320925	0.289988
B	0.533982	0.435573
C	0.562847	0.449775
D	0.336031	0.307021
E	0.28849	0.347154
F	0.386241	0.49739
G	0.453493	0.550702
Echo1	0.334217	0.386467
EK1	0.257956	0.169057
EK2	0.329283	0.333995
R4	0.359281	0.279373
Echo2	0.340391	0.396476
EK3	0.349241	0.360009
EK4	0.273279	0.243078

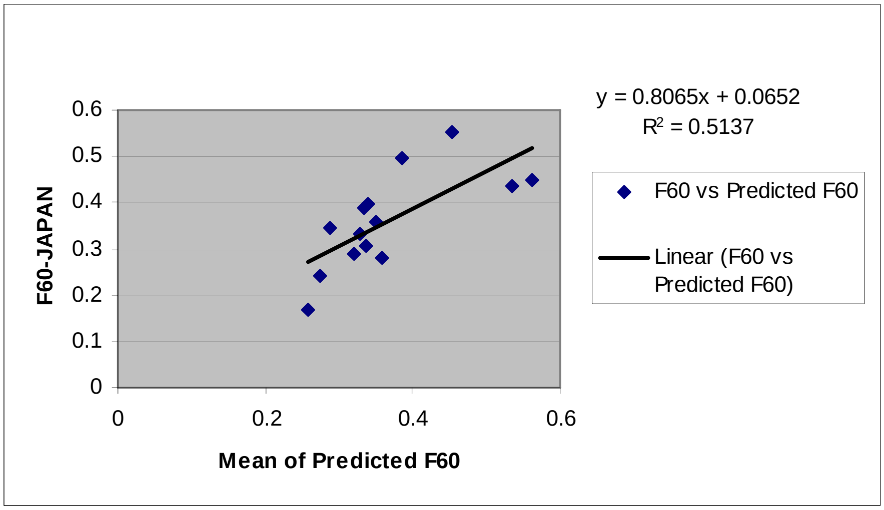

Figure 19 DFT F60 vs. Mean of Predicted F60 (NASA GT at 95 km/hr, DFT-Japan)

Table 19 Mean of Predicted F60 and F60-PTI Values for NASA GT at 65 km/hr

NASA GT at 65 km/hr, DFT-PTI		
Surface	Mean of Predicted F60	F60-PTI
A	0.288177	0.279806
B	0.493327	0.429147
C	0.502738	0.455747
D	0.313054	0.292853
E	0.279727	0.337679
F	0.440597	0.50926
G	0.524614	0.559099
Echo1	0.328382	0.380571
EK1	0.198353	0.159461
EK2	0.311962	0.320564
R4	0.348945	0.271381
Echo2	0.354078	0.383144
EK3	0.334395	0.326104
EK4	0.242893	0.245092

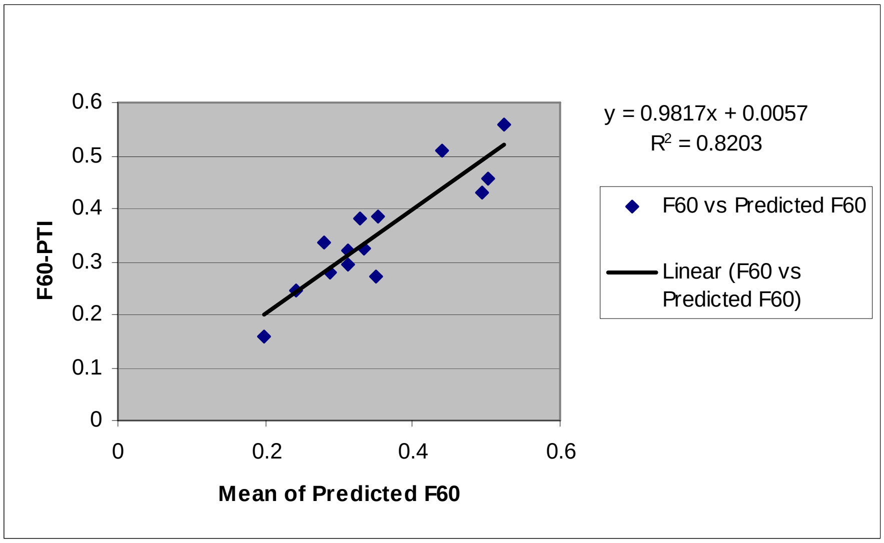

Figure 20 DFT F60 vs. Mean of Predicted F60 (NASA GT at 65 km/hr, DFT-PTI)

Table 20 Mean of Predicted F60 and F60-PTI Values for NASA GT at 95 km/hr

NASA GT at 95 km/hr, DFT-PTI		
Surface	Mean of Predicted F60	F60-PTI
A	0.304298	0.279806
B	0.543676	0.429147
C	0.552365	0.455747
D	0.327383	0.292853
E	0.275985	0.337679
F	0.386852	0.50926
G	0.457053	0.559099
Echo1	0.328075	0.380571
EK1	0.242745	0.159461
EK2	0.3195	0.320564
R4	0.352813	0.271381
Echo2	0.331698	0.383144
EK3	0.336572	0.326104
EK4	0.258657	0.245092

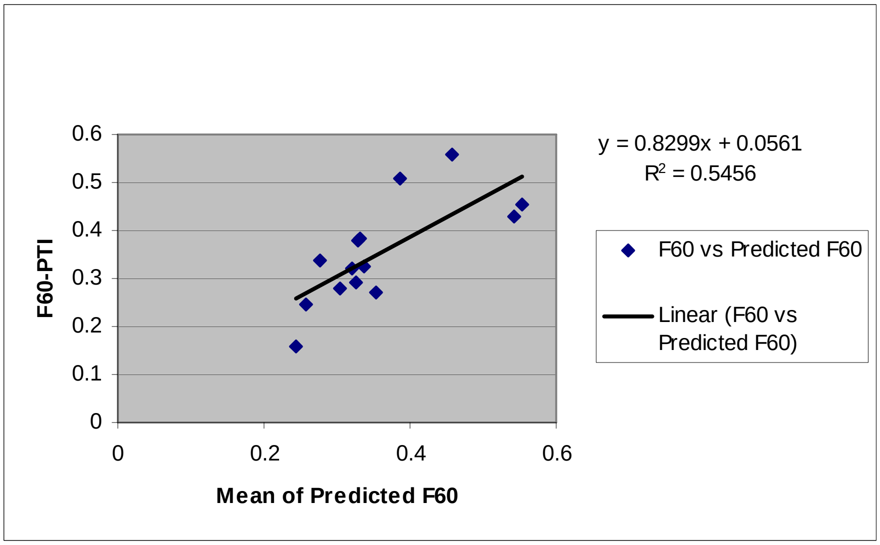

Figure 21 DFT F60 vs. Mean of Predicted F60 (NASA GT at 95 km/hr, DFT-PTI)

Table 21 t-test Results for NASA GT at 65 km/hr and 95 km/hr with DFT-VT, Japan and PTI

NASA GT						
DFT	VT		Japan		PTI	
Speed (km/hr)	65	95	65	95	65	95
t_o	0.024	0.125	0.043	0.155	0.021	0.125
Degree of freedom	25.86	25.71	25.8	25.64	25.83	25.65
LOC	90%	90%	90%	90%	90%	90%
t-critical	1.315	1.315	1.315	1.315	1.315	1.315

Table 22 t-test Results for FAA RFT at 65 km/hr and 95 km/hr with DFT-VT, Japan and PTI

FAA RFT						
DFT	VT		Japan		PTI	
Speed (km/hr)	65	95	65	95	65	95
t_o	0.052	0.087	0.073	0.111	0.052	0.089
Degree of freedom	25.91	25.84	25.86	25.78	25.89	25.82
LOC	90%	90%	90%	90%	90%	90%
t-critical	1.315	1.315	1.315	1.315	1.315	1.315

Approach 2:

In this validation procedure the predicted range of F60 is considered as a normal distribution. Although F60 does not need to follow a normal distribution, in order to predict Z-values for DFT F60 with respect to DFT F60, F60 is assumed to follow a normal distribution. Then the Z –values are computed to locate the position of the measured DFT F60 with respect to the predicted F60. It is known that Z-values with an absolute magnitude higher than about 4.0 correspond to measured values which do not fall within the predicted domain.

The Z-values obtained for each left out surface are shown in Tables 23, 24 and 25 with DFT-VT, Japan and PTI respectively. The absolute Z-values corresponding to several surfaces (E, F, Echo1, R4, and Echo2) are greater than 4.0 showing that the means of measured F60 do not lie in the predicted F60 range. This anomaly in the values of Z shows the presence of an error. The possible sources of this error are discussed below.

Table 23 Z - Values for NASA GT at 65 km/hr and 95 km/hr with Respect to DFT-VT

NASA GT, DFT-VT		
Z-Values		
	At 65 km/hr	At 95 km/hr
A	-2.734	-3.32808
B	-3.26694	-2.15378
C	-3.89403	-2.34326
D	-4.32473	-4.43086
E	9.780506	6.108974
F	7.336648	9.203925
G	0.818629	2.657498
Echo1	8.425362	5.410487
EK1	-3.11808	-4.56925
EK2	2.070625	0.595064
R4	-13.4441	-8.16776
Echo2	5.154237	5.632148
EK3	0.545695	0.054914
EK4	0.428963	-0.80615

Table 24 Z - Values for NASA GT at 65 km/hr and 95 km/hr with Respect to DFT-Japan

NASA GT, DFT-Japan		
Z-Values		
Surface	At 65 km/hr	At 95 km/hr
A	-2.44291	-2.90385
B	-3.50566	-2.11505
C	-4.36602	-2.32699
D	-2.16007	-2.89684
E	9.143463	5.182773
F	6.1077	8.19009
G	1.560032	3.337786
Echo1	8.892358	5.481526
EK1	-3.08823	-4.58592
EK2	1.835077	0.470105
R4	-12.6637	-7.78365
Echo2	4.932331	5.779301
EK3	1.46867	1.036551
EK4	-1.1875	-1.69694

Table 25 Z - Values for NASA GT at 65 km/hr and 95 km/hr with Respect to DFT-PTI

NASA GT, DFT-PTI		
Z-values		
Surface	At 65 km/hr	At 95 km/hr
A	-1.15533	-2.32171
B	-4.87454	-2.6224
C	-2.95866	-1.96661
D	-3.07658	-3.53971
E	10.32233	5.871776
F	6.385201	8.448261
G	1.571269	3.407478
Echo1	8.698641	5.523046
EK1	-3.05973	-4.61073
EK2	1.317826	0.108849
R4	-13.3833	-7.86875
Echo2	4.273046	5.31191
EK3	-1.2722	-1.03746
EK4	0.226473	-0.82307

Similar results for FAA RFT are shown in the Appendix A.

4.2.1. Speed Sensitivity

The validation results show that the A and B values obtained from 65 km/hr speed results provide a better correlation. Therefore A and B values at 65 km/hr can be assumed as calibration constants for NASA GT. Furthermore when the A and B values corresponding to 65 km/hr are used to predict the range of F60 from 95 km/hr data, the mean of the predicted F60 values agreed better with the DFT F60 (the standard) than the F60 predicted using A and B corresponding to 95 km/hr. Table 26 shows the correlation of predicted F60 at 95 km/hr and the DFT F60 using A and B values obtained from both 95 km/hr and 65 km/hr.

Table 26 Correlation between Predicted F60 and DFT F60 for NASA GT at 95 km/hr

DFT	VT	JAPAN	PTI
Predicted F60 Using A,B from 95 km/hr Data	0.5624	0.5137	0.5456
Predicted F60 Using A,B from 65 km/hr Data	0.6879	0.681	0.6595

4.2.2. Raw Data Verification

Continuous friction measuring equipment measure friction values at every 1 ft intervals. Therefore raw data for each surface was checked to see whether there is any abnormal variation between the average friction value for each surface and the raw data obtained at intervals of 1 ft. Figure 22 and 23 show the raw data and the averages for surfaces with excessive and normal Z-values respectively. Since there is no obvious difference between Figure 22 and Figure 23 it was concluded that the variation of raw data does not explain the excessive Z-values.

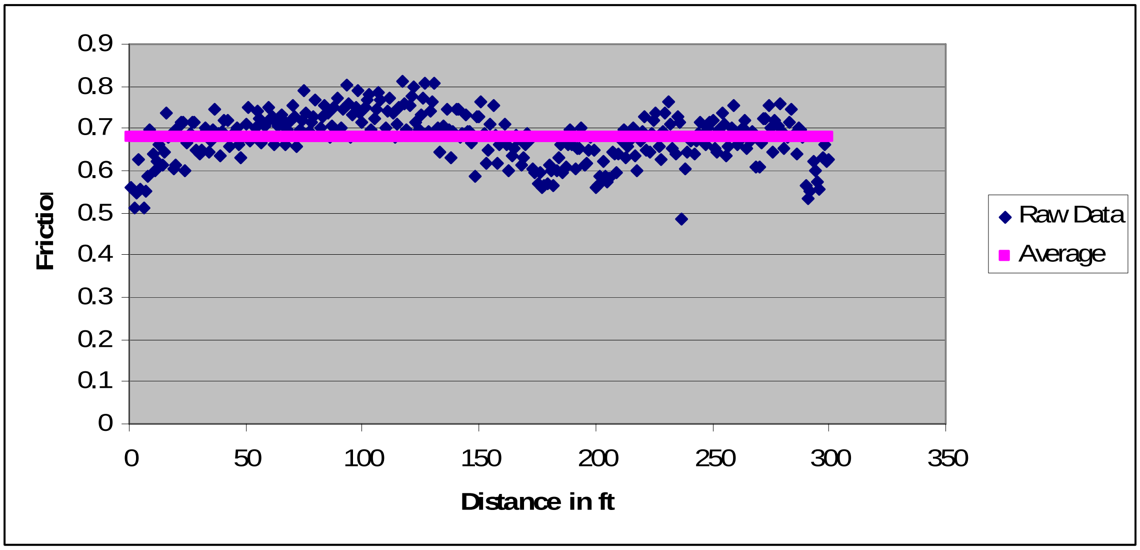

Figure 22 Friction Values from Raw Data for Surface with an Excessive Z - value (R4)

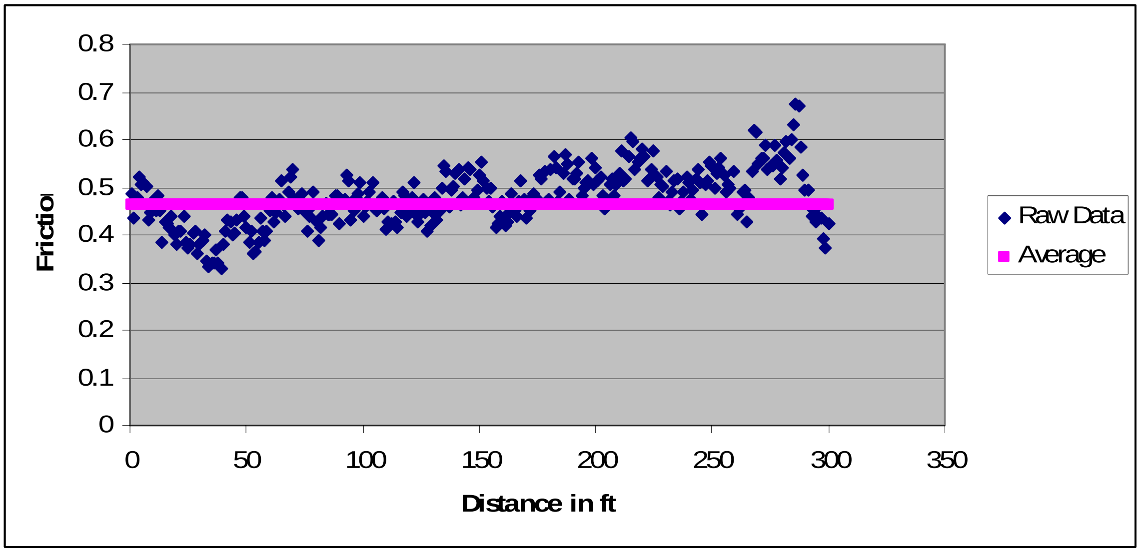

Figure 23 Friction Values from Raw Data for Surface with a Normal Z - Value (EK3)

4.2.3. Check for Effectiveness of Sp and MPD Linear Relationship

The ASTM Standard procedure emphasizes that adjusted friction at 60 km/hr slip speed must not depend on the operating speed. However results of t-test (Section 2.1.1) show that the FR60 obtained from FR65 and FR95 are significantly different from each other. By assuming FR60 to be a constant for the above two speeds a back-calculation procedure was performed to observe the speed constant Sp vs. MPD relationship. It was observed that while a linear relationship yielded a R^2 values of 0.5, a polynomial of degree 6 (Equation (7)) yielded a correlation of 0.974.

$$\begin{aligned} Sp &= 1088.3 * MPD^6 - 7172 * MPD^5 + 17887 * MPD^4 \\ &- 21230 * MPD^3 + 12436 * MPD^2 - 3323.3 * MPD + 312.11 \end{aligned} \tag{7}$$

Hence it is suspected that one reason for obtaining abnormally high Z values during validation could be due to the inapplicability of the general linear relationship to any one given equipment and a set of test surfaces as seen in Equation (3).

4.2.4. Computation of Sp and MPD Relationship

In Figure 24 the author plotted the Sp for three equipment (NASA GT, FAA RFT and VA E274) vs. MPD for all 14 test surfaces. The best fit line given by Equation (8) and the line corresponding to Equation (3) seem to agree to some degree.

$$Sp = 25.48 + 69.163 * MPD \tag{8}$$

However the R^2 value corresponding to Equation (8) is only 0.10 showing that it is a very approximate general relationship for the equipment (NASA GT, FAA RFT and VA E274). Hence the same argument applies from Equation (3) as well.

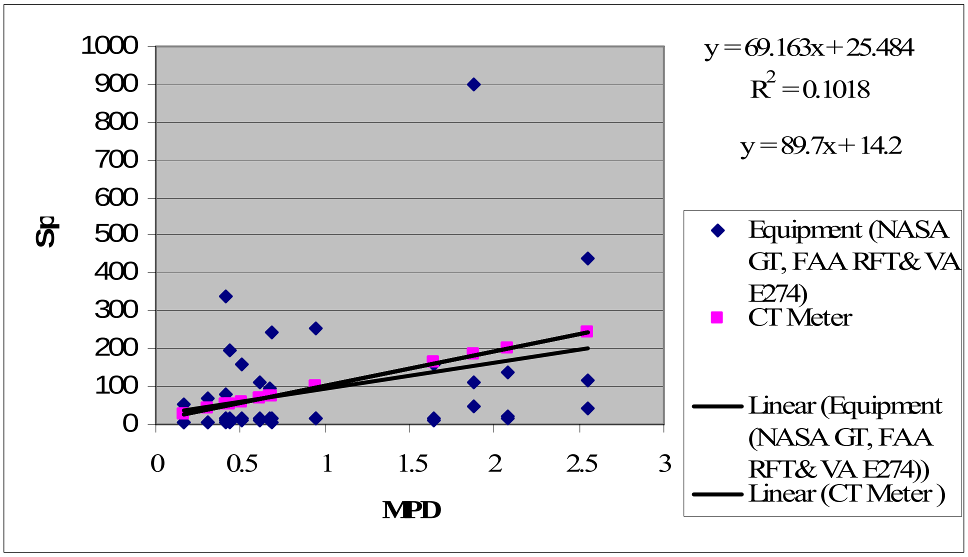

Figure 24 MPD vs. Sp Using all the 14 Surfaces and Three Equipment (NASA GT, FAA RFT and VA E274)

4.2.5. Alternative Calculation for more Accurate Sp and MPD Relationship

In this process two equipment NASA GT and FAA RFT were considered with DFT-VT data. If one assumes the FR60 resulting from FR65 and FR95 to be the same, Equation (3) yields

$$\frac{(S2 - S1)}{LN(\frac{FR65}{FR95})} = Sp \tag{9}$$

Where S_2= 95*0.145

S_1= 65*0.145

From Equation (9) MPD can be expressed in terms of a multiple linear regression equation which is developed with the Sp from two equipment as independent variables and MPD obtained from the CT meter- VT as the dependent variable.

$$MPD = -0.2049-0.0095*(Sp)_1+0.0781*(Sp)_2 \tag{10}$$

Where $(Sp)_1$ is obtained from NASA GT and $(Sp)_2$ is obtained from FAA RFT.

For the data analysis of NASA GT, $(Sp)_2$ becomes zero. Then the Equation (10) is reduced to Equation (11) and Sp for NASA GT can be computed from MPD.

$$MPD= -0.2049- 0.0095*(Sp)_1 \tag{11}$$

For the data analysis of FAA RFT, $(Sp)_2$ becomes zero. Then the Equation (10) is reduced to Equation (12) and Sp for FAA RFT can be computed from MPD.

$$MPD = -0.2049 + 0.0781*(Sp)_2 \tag{12}$$

Then the modified method of data analysis described in Chapter 4 was performed with the Sp value obtained from the multiple linear regression equation. The minimum, maximum and mean of A, B for all the possible 14 trials are shown in Table 27 for 65 km/hr with DFT-VT. While the minimum, maximum, mean and Z-values of the predicted F60 are shown in Table 28 for 65 km/hr with DFT-VT.

Table 27 Minimum, Maximum, Mean and Standard Deviation of A, B for NASA GT at 65 -km/hr with DFT-VT

Calibration Constants	A				B			
Surface	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
A	-0.0890	0.8439	0.2558	0.1568	-0.4394	0.5025	0.1095	0.1488
B	0.0376	0.8997	0.2744	0.1539	-0.4977	0.3402	0.0754	0.1404
C	0.0067	0.9066	0.2564	0.1545	-0.5038	0.3692	0.0916	0.1411
D	-0.0890	0.8571	0.2778	0.1560	-0.4507	0.5025	0.0860	0.1466
E	-0.0890	0.9834	0.2859	0.1644	-0.5833	0.5025	0.0740	0.1560
F	0.0470	0.8022	0.2605	0.1389	-0.4149	0.3219	0.0818	0.1273
G	0.0996	0.8838	0.2954	0.1442	-0.4980	0.2707	0.0467	0.1313
Echo1	0.0521	0.9580	0.2954	0.1613	-0.5482	0.3324	0.0598	0.1472
EK1	0.3318	1.0015	0.5541	0.1379	-0.5833	0.0353	-0.175	0.1232
EK2	-0.0890	1.0015	0.2546	0.1935	-0.5833	0.5025	0.1083	0.1862
R4	0.0982	1.0015	0.3776	0.2282	-0.5833	0.2900	-0.015	0.2083
Echo2	0.0353	0.9115	0.3010	0.1540	-0.5109	0.3551	0.0546	0.1425
EK3	0.0216	0.9008	0.2981	0.1557	-0.4945	0.3740	0.0612	0.1441
EK4	0.0390	1.0015	0.3173	0.1694	-0.5788	0.3628	0.0493	0.1560

Table 28 Minimum, Maximum, Mean and Standard Deviation of Predicted F60 and Z -Values of DFT F60 with Respect to Predicted F60

F60- Predicted					
Surface	Min	Max	Mean	Std dev	Z- value
A	0.3161	0.5146	0.3873	0.0297	-3.9717
B	0.2780	0.4576	0.3441	0.0289	3.4475
C	0.2701	0.4792	0.3369	0.0342	3.6532
D	0.3318	0.4822	0.3756	0.0222	-4.2224
E	0.2801	0.5170	0.3751	0.0315	-1.1249
F	0.2837	0.4232	0.3388	0.0227	8.7677
G	0.2974	0.3914	0.3437	0.0163	12.7299
Echo1	0.2900	0.4600	0.3519	0.0278	0.9904
EK1	0.3345	0.6481	0.4468	0.0635	-4.5451
EK2	0.1925	0.5925	0.4014	0.0629	-1.2601
R4	0.2753	0.5590	0.3688	0.0704	-1.4606
Echo2	0.3117	0.4221	0.3601	0.0184	1.2411
EK3	0.3132	0.4189	0.3628	0.0186	-1.5601
EK4	0.3123	0.4389	0.3660	0.0228	-5.5190

Comparison of Table 25 with Table 23 shows that the Z-values would be more realistic for the new Sp vs. MPD Equation (10).

CHAPTER FIVE

CONCLUSIONS

A comprehensive analytical study was performed to investigate the applicability of the ASTM IFI computational procedure for standardization of friction measurements from different CFMEs. The following conclusions can be reached based on the above investigation.

(a) The investigation revealed that the friction value adjusted to 60 km/hr slip speed (FR60) based on measurements at 65 km/hr and 95 km/hr (FR65 and FR95) differed consistently for all CFMEs and runways. A significance test conducted in this research showed that FR60 from FR65 and FR95 are significantly different from each other. Therefore the calibration constants A and B would vary with the testing speed. These results also show that the ASTM calibration is speed dependent.

(b) When 10 runway surfaces were selected out of 14 for calibration and the remaining 4 surfaces left for validation, the results showed that the predicted friction values obtained from the testing speed of 65 km/hr were more accurate than those from the testing speed of 95 km/hr.

(c) ASTM standard procedure advocates the use of single A and B calibration constants for a given equipment which results in a single F60 prediction causing an uncertainty in the actual friction value on the surface. This uncertainty can be addressed by treating A and B as random variables and predicting the F60 as a random variable within a certain level of confidence.

(d) Since the random variation of the calibration constants are represented by normal distributions, the error (with respect to the corresponding DFT reading) in each validation trial can be represented by a Z-value. The Z values for some surfaces show excessive magnitudes indicating a poor agreement.

(e) Inaccurate prediction of IFI (with respect to DFT) for some surfaces (item d) and the dependency of FR60 on the testing speed (item a) can be attributed to the overly simplified IFI computation protocol laid out in the ASTM IFI standard.

(f) One critical simplification could be involved in the general linear Sp vs. MPD relationship that appears to have been derived to suit a multitude of equipment and a number of test surfaces. This relationship is equipment dependent and its inapplicability to particular equipment was amply demonstrated in this study by back computing a number of alternative Sp vs. MPD relationships.

REFERENCES

1. ASTM E1960-03: “Standard Practice for Calculating International Friction Index of a Pavement Surface”

2. Thomas J.Yager, NASA Langley Research Center. “AN OVERVIEW OF THE JOINT FAA/NASA AIRCRAFT/GROUND VEHICLE RUNWAY FRICTION PROGRAM”

3. NASA Wallops Tire / Runway Friction workshop Data, May 2005

4. NASA Wallops Tire / Runway Friction workshop Data, May 2006

5. NASA Wallops Tire / Runway Friction workshop Data, May 2007

APPENDICES

Appendix A: Data Analysis Results for FAA RFT

Table 29 FAA RFT Calibration Constants

Speed	65 km/hr			95 km/hr		
DFT	VT	Japan	PTI	VT	Japan	PTI
A	0.155	0.167	0.189	0.179	0.196	0.204
B	0.523	0.498	0.454	0.544	0.506	0.484
R^2	0.84	0.8	0.7	0.74	0.7	0.64

Table 30 Correlation between Computed F60 and DFT F60

FAA RFT						
DFT	VT		Japan		PTI	
Operating Speed	65 km/hr	95 km/hr	65 km/hr	95 km/hr	65 km/hr	95 km/hr
Correlation between F60 (DFT) and F60 (Computed)	0.50	0.391	0.6342	0.4921	0.5584	0.4363

Appendix A: (Continued)

Table 31 Z – Values for FAA RFT at 65 km/hr and 95 km/hr with Respect to DFT-VT, Japan and PTI

NASA GT						
Z-Values						
DFT	VT		JAPAN		PTI	
Operating Speed	65 km/hr	95 km/hr	65 km/hr	95 km/hr	65 km/hr	95 km/hr
A	-2.734	-3.32808	-2.44291	-2.90385	-1.15533	-2.32171
B	-3.26694	-2.15378	-3.50566	-2.11505	-4.87454	-2.6224
C	-3.89403	-2.34326	-4.36602	-2.32699	-2.95866	-1.96661
D	-4.32473	-4.43086	-2.16007	-2.89684	-3.07658	-3.53971
E	9.780506	6.108974	9.143463	5.182773	10.32233	5.871776
F	7.336648	9.203925	6.1077	8.19009	6.385201	8.448261
G	0.818629	2.657498	1.560032	3.337786	1.571269	3.407478
Echo1	8.425362	5.410487	8.892358	5.481526	8.698641	5.523046
EK1	-3.11808	-4.56925	-3.08823	-4.58592	-3.05973	-4.61073
EK2	2.070625	0.595064	1.835077	0.470105	1.317826	0.108849
R4	-13.4441	-8.16776	-12.6637	-7.78365	-13.3833	-7.86875
Echo2	5.154237	5.632148	4.932331	5.779301	4.273046	5.31191
EK3	0.545695	0.054914	1.46867	1.036551	-1.2722	-1.03746
EK4	0.428963	-0.80615	-1.1875	-1.69694	0.226473	-0.82307