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Repeatability and Reproducibility of Saab Friction Measurement Devices in Self-Wet Mode

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Transportation Development Centre of Transport Canada,
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By
Transportation Infrastructure Consulting and Services Ltp.
TICS. Ltp

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16. Abstract

A series of tests to establish the repeatability and reproducibility statistics of the Saab friction tester were conducted in March 2002 at Prague Airport. The basic issue for the study was to analyze the behaviour of the different Saab friction measurement devices in self-wet mode on different surfaces with respect to repeatability, reproducibility, and stability.

The surface areas measured during the data collection were on the south end of Runway 04/22 of the PRAHA/Ruzene. The surface was divided into three test sections: (A) the section of bare asphalt; (PAINT) the paint section that was defined to fall onto the touchdown paint-marks; and (C) the third section of bare asphalt.

Nine Saab friction measurement devices from four different manufacturers (ASFT, Sarsys, Safegate, Saab), a BV-11, the IRV and the Tatra friction measurement devices participated in the test session.

The procedures employed in this study were the standard data analysis procedures in the ASTM E691 and ISO 5725 standards.

It was determined that the participating Saab friction measurement devices in self-wet mode produced a repeatability uncertainty of 0.07, a reproducibility standard deviation of 0.10, a repeatability coefficient of variation of 6.6%, and a reproducibility coefficient of variation of 11.4%.

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16. Résumé

En mars 2002, l'aéroport de Prague a été le théâtre d'essais qui visaient à établir la répétabilité et la reproductibilité des valeurs mesurées par le glissancemètre de Saab. Cette étude s'articulait principalement autour de l'analyse du comportement des différents appareils de mesure du frottement de type Saab, en mode d'arrosage automatique, sur diverses surfaces. Une attention particulière a été accordée à la répétabilité, la reproductibilité et la constance des données colligées.

Les aires d'essais qui ont servi à la collecte des données se trouvaient à l'extrémité sud de la piste 04/22 de l'aéroport Praha/Ruzyne. La surface de la piste était divisée en trois sections : la section A, constituée exclusivement de revêtement bitumineux; la section PAINT, qui chevauchait la partie de la piste où l'on retrouve les marques de toucher des roues peintes sur la chaussée et la section C, elle aussi exclusivement en revêtement bitumineux.

Dans le cadre de cette étude, neuf glissancemètres de Saab fournis par quatre fabricants différents (ASFT, Sarsys, Safegate et Saab), ainsi que les véhicules BV-11, IRV et Tatra, ont été mis à contribution.

Les procédures d'analyse des données utilisées lors de cette étude respectaient les normes ASTM E691 et ISO 5725.

Il a été démontré que les données produites par les glissancemètres de marque Saab, en mode d'arrosage automatique, affichaient une incertitude de répétabilité de 0,07, un écart-type de reproductibilité de 0,10, un coefficient de variation de répétabilité de 6,6 % et un coefficient de variation de reproductibilité de 11,4 %.

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EXECUTIVE SUMMARY

Under severe winter conditions several countries rigorously impose limits and weight penalties for aircraft takeoffs and landings. These limits depend on the weather conditions and the runway conditions, which are established by visual inspection and the measurement of runway friction coefficient using ground friction measurement equipment.

It is expected and indeed is proven that the aircraft braking friction coefficients of contaminated runways are different for aircraft than those reported by the ground equipment on which the penalties and limits are based. Measuring the capability of the runway surface to provide aircraft tire-braking action is fundamental to airport aviation safety, especially under winter conditions. Thus, a system directly capable of determining the aircraft braking friction coefficient would represent a direct and substantial benefit for the aviation industry.

The wide range of different ground friction measurement devices used today by different countries and the large number of differing procedures in measuring winter surface friction result in non-harmonized, high scatter frictional parameters on winter contaminated surfaces and, in fact, on all contaminated surfaces.

It has been established that the frictional values reported by different types of ground friction measurement equipment are substantially different. In fact, the same type and manufacture, and even the same model of equipment report highly scattered frictional data. Calibration and measurement procedures are different for different types of devices. The repeatability and reproducibility scatter of each type of ground friction measurement device is therefore amplified and the spread of friction measurement values among different equipment types is significant. It is necessary to develop a practical and simple solution to harmonize the different groups and families of ground friction measurement equipment for winter operation in order to ensure the meaningful and uniform reporting of winter runway surface friction across borders and regions.

The Joint Winter Runway Friction Measurement Program has conducted uncertainty analyses for many different friction measurement devices. This study focused on the exploration of the uncertainty factors of repeatability and reproducibility of the Saab friction measurement equipment family based on the fixed slip measurement principle.

The original scope of the data collection at the Prague airport test site was to quantify uncertainties in the measurement process of the Saab friction measurement equipment that would be difficult to quantify under conditions of actual measurements.

The procedures employed in this study were the standard data analysis procedures in the ASTM E691 and ISO 5725 standards that are intended for test agencies and scientific laboratories that report results of measurements from ongoing or well-documented processes [1].

For computational procedures, this study followed the ISO approach [2] to computing and combining components of uncertainty. To this basic structure was added a statistical framework for estimating individual components.

The original scope of the test was to conduct measurements on numerous different surfaces, mainly winter surfaces, but due to mild weather it was not possible. Accordingly, the

measurements analyzed in this study were made on a limited selection of surfaces. Therefore, these results can only be used with careful consideration as a general evaluation of the participating measurement devices.

It was determined that the repeatability of the participating Saab friction measurement devices in this study produced an uncertainty of 0.07 average repeatability standard deviation friction units on a scale of 0 to 1.00, with a maximum uncertainty deviation of 0.08 and the minimum uncertainty 0.06. Thus, the uncertainty content of the Saab friction measurement units as a whole under self-wet conditions is an average of 7% of the maximum scale.

The family of the Saab measurement equipment produced relatively uniform and well distributed uncertainty characteristics with regard to the differences between the different measurement units. Thus, the repeatability uncertainty statistical parameters gave very similar characteristics for the participating measurement equipment.

The measurement devices reported a relatively wide range of average friction values for the different surfaces. The calculated average of the absolute differences between the maximum and minimum friction values reported by the different equipment for the surfaces A, PAINT, and C were 0.16, 0.12, and 0.12, respectively.

The devices and surfaces included in this study produced an average reproducibility standard deviation equal to 0.10. This is an average value of the reproducibility standard deviation of all devices for each measurement session. As one would expect, the repeatability of the devices was better than the reproducibility of the device family.

Relating the variability with the friction level by using the coefficient of variation provides compatibility of this study to other repeatability studies. The average repeatability coefficient of variation for all devices and surfaces combined was 6.6% and the corresponding average reproducibility coefficient of variation was 11.4%.

1.1 References

1. NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/

2. Guide to the Expression of Uncertainty in Measurement (1993, corrected and reprinted, 1995). ISBN 91-67-10188-9, 1st ed. ISO, Case postale 56, CH-1211, Genève 20, Switzerland, 101 pages. Available from the American National Standards Institute, 11 West 42nd Street, New York, NY 10036, U.S.A. Telephone: 1-212-642-4900.

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De nombreux pays imposent des limites de poids aux avions qui effectuent des manœuvres de décollage et d'atterrissage dans les aéroports, en hiver. Ces limites imposées par les autorités aéroportuaires varient en fonction des conditions météorologiques et de l'état de la surface de la piste, ces paramètres étant établis par une inspection visuelle de la chaussée et à l'aide du coefficient de frottement calculé par les glissancemètres.

Il est prouvé que les coefficients de frottement d'une piste contaminée, au freinage d'un aéronef, diffèrent de ceux calculés par les appareils de mesure du frottement et sur lesquels s'appuient les limites de poids imposées par les autorités. Connaître l'adhérence des pneus d'un avion au freinage est essentiel à la sûreté des opérations aériennes aux aéroports, particulièrement en hiver. Ainsi, un système capable de déterminer rapidement le coefficient de frottement au freinage d'un aéronef constitue un avantage certain pour l'industrie aéronautique.

Actuellement, de nombreux pays ont recours à une vaste gamme d'appareils et de procédures pour mesurer la glissance des pistes et déterminer le coefficient de frottement des pneus d'aéronefs. Il en résulte des données non harmonisées et diffuses sur la glissance des pistes contaminées par des dépôts de toutes sortes, particulièrement en hiver.

La preuve a été faite que des appareils de mesure du frottement de conception ou de types différents produisent des coefficients de frottement différents. On a aussi établi que même les appareils d'un même type produisent des coefficients de frottement assez différents. Il convient de signaler que les procédures d'étalonnage et de mesure varient selon le type d'appareil, ce qui a pour effet d'accentuer la dispersion des données et de réduire leur répétabilité et leur reproductibilité. Il en va de même pour la variabilité des coefficients de frottement calculés par les appareils de types différents. Une solution simple et pratique doit être mise au point, qui permettrait d'harmoniser les différents groupes d'instruments de mesure de la glissance des pistes en hiver pour s'assurer que les données des différents pays et régions sont uniformes.

Les chercheurs participant au Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver ont soumis bon nombre d'appareils de mesure de la glissance des pistes à des analyses d'incertitude. Cette démarche visait à étudier les facteurs d'incertitude associés à la répétabilité et à la reproductibilité des résultats calculés par les glissancemètres de Saab à taux de glissement constant.

La collecte de données initiale effectuée sur le site d'essai de l'aéroport de Prague visait à quantifier le degré d'incertitude des processus de mesure des appareils Saab, tâche difficile à réaliser en situation réelle de mesurages.

Cette étude s'appuie sur les normes ASTM E691 et ISO 5725 portant sur les procédures d'analyse des données. Celles-ci sont destinées aux laboratoires scientifiques et aux organismes chargés de réaliser des essais et de présenter les résultats de mesures dans le cadre de processus en cours ou bien documentés [1].

En ce qui concerne les procédures de calcul, la présente étude a respecté l'approche ISO [2] relative au traitement et à la combinaison d'éléments d'incertitude. Un cadre statistique a été ajouté à cette structure pour l'évaluation des éléments individuels.

La portée initiale des essais visait à effectuer des mesures sur diverses surfaces, principalement des pistes en période hivernale, mais le temps doux a empêché la réalisation de ces essais. Par conséquent, les mesures analysées dans ce rapport ont été menées sur un éventail limité de surfaces. Pour cette raison, ces résultats ne peuvent être interprétés qu'avec beaucoup de vigilance, dans le cadre d'une évaluation globale des appareils de mesure soumis aux essais.

Il a été établi que l'écart-type moyen de répétabilité pour les glissancemètres Saab, faisant l'objet de cette étude, était de 0,07 sur une échelle variant de 0 à 1,00; le coefficient maximal d'incertitude étant de 0,08 et le coefficient minimal de 0,06. Ainsi, l'incertitude moyenne des données produites par le glissancemètre Saab, en mode d'arrosage automatique, est de 7 %.

Les coefficients d'incertitude des appareils de mesure de type Saab étaient relativement uniformes et bien répartis, comparativement à ceux des appareils de types différents. Ainsi, les statistiques relatives à l'incertitude de répétabilité étaient semblables d'un appareil de mesure à l'autre.

Les coefficients de frottement moyens calculés par les glissancemètres, sur différentes surfaces, étaient très variables. L'écart moyen entre les valeurs de frottement maximale et minimale pour les surfaces A, PAINT et C était de 0,16, 0,12 et 0,12, respectivement.

L'écart-type de reproductibilité pour l'ensemble des surfaces et des appareils utilisés dans le cadre de cette étude est de 0,10. Il s'agit de la variation moyenne observée dans les mesures prises par l'ensemble des appareils. Comme prévu, la répétabilité de l'ensemble des appareils a été meilleure que la reproductibilité du groupe d'appareils d'un même type.

Il est possible de rendre cette étude compatible avec d'autres études de répétabilité en mettant la variabilité en relation avec le taux de frottement au moyen du coefficient de variation. L'écart-type moyen de répétabilité pour l'ensemble des appareils et des surfaces était de 6,6 %; l'écart-type de reproductibilité correspondant, de 11,4 %.

1.2 Références

1. NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/

2. Guide to the Expression of Uncertainty in Measurement (1993, corrigé et réimprimé en 1995). ISBN 91-67-10188-9, 1st ed. ISO, Case postale 56, CH-1211, Genève 20, Suisse, 101 pages. Disponible auprès de l'American National Standards Institute, 11 West 42nd Street, New York, NY 10036, É.-U. Téléphone : 1-212-642-4900.

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ACRONYMS AND DEFINITIONS

ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration, USA
IMAG	Instrument de Mesure Automatique de Glissance
IRFI	International Runway Friction Index
IRV	IRFI Reference Vehicle. A dedicated IMAG device serving as a reference device for the International Runway Friction Index.
ISO	International Organization for Standardization
JWRFMP	Joint Winter Runway Friction Measurement Program
PIARC	World Road Association, formerly Permanent International Association of Road Congresses
SFT	Surface SAAB Friction Tester

1 INTRODUCTION

Under severe winter conditions several countries rigorously impose limits and weight penalties for aircraft takeoffs and landings. These limits depend on the weather conditions and the runway conditions, which are established by visual inspection and many cases by the measurement of runway friction coefficient using ground friction measurement equipment.

It is expected and indeed is proven that the aircraft braking friction coefficients of contaminated runways are different for aircraft than those reported by the ground equipment on which the penalties and limits are based. Measuring the capability of the runway surface to provide aircraft tire-braking action is fundamental to airport aviation safety, especially under winter conditions. Thus, a system directly capable of determining the aircraft braking friction coefficient would represent a direct and substantial benefit for the aviation industry.

The wide range of different ground friction measurement devices used today by different countries and the large number of differing procedures followed in measuring winter surface friction result in non-harmonized, high scatter frictional parameters on winter contaminated surfaces and, in fact, on all contaminated surfaces.

It has been established that the frictional values reported by different types of ground friction measurement equipment are substantially different. In fact, the same type and manufacture, and even the same model of equipment report highly scattered frictional data. Calibration and measurement procedures are different for different types of devices. The repeatability and reproducibility scatter of each type of ground friction measurement device is therefore amplified and the variation of friction measurement values among different equipment types are significant. Development of a practical and simple solution to harmonize the different groups and families of ground friction measurement equipment in order to ensure the meaningful and uniform reporting across borders and regions. Building on the harmonized friction characteristics, models and procedures to compute an indication of aircraft braking performance can be formulated and validated.

In 1995, the Joint Winter Runway Friction Measurement Program (JWRFMP) was established with the aim to improve aircraft ground operations under winter conditions. The program was established by Transport Canada, the U.S. National Aeronautics and Space Administration, National Research Council Canada, and the U.S. Federal Aviation Administration (FAA). The primary objective of the international program that is now supported by many different countries is to perform instrumented aircraft and ground vehicle tests to develop simple and practical solutions for ground friction measurement harmonization and prediction of aircraft braking performance on winter contaminated surfaces. Harmonization will enable the reporting of friction data to a unified common index worldwide, which will then be used to predict aircraft braking performance. This report addresses the repeatability and reproducibility of statistics of the Saab friction measurement equipment family in self-wet mode as tested in Prague 2002.

2 PROGRAM OBJECTIVE AND STUDY OBJECTIVE

The objective of the JWRFMP is to (a) analyze and characterize the behaviour of different ground friction measurement devices on winter contaminated runways, (b) develop simple mathematical and operational procedures to harmonize ground friction measurements based on the outcome of the analysis, (c) develop a reporting and analysis procedure to provide aircraft braking performance indicators from ground friction measurement results using the harmonized friction characteristic parameters.

The objective of this study is to establish the repeatability and reproducibility statistics for the Saab friction measurement devices that participated in the 2002 Prague Airport testing session in self-wet mode.

3 SCOPE OF THE STUDY

During the years of testing conducted within the framework of the JWRFMP, large amounts of frictional information were collected using a number of different friction measurement devices. The scientific analysis of the database built from the measurements performed on a variety of different winter-contaminated, bare and dry, and wet surface conditions is under way.

In order to be able to draw conclusive conclusions from the analyzed data and to make recommendations to harmonize friction measurement equipment, it is essential to examine the behaviour of the different measurement devices. A very significant part of the exploration of the measurement devices is to research the variability of the measurements for the different measurement devices and to analyze the uncertainty of the measurements.

The analysis of variability and uncertainty involves the investigation of the repeatability and reproducibility of the friction measurements with respect to measurement conditions and measurement principles.

The JWRFMP has conducted the uncertainty analyses for many different measurement devices. This study focused on the exploration of the uncertainty factors of repeatability and reproducibility of the Saab friction measurement equipment family based on the fixed slip measurement principle.

The scope of the data collection at the Prague Airport test site permitted conducting the present study to quantify uncertainties in the measurement process of the Saab friction measurement equipment that would be difficult to quantify under conditions of actual measurement.

4 ISSUES FOR UNCERTAINTY ANALYSIS OF MEASUREMENTS

Evaluation of uncertainty in general is a very complex process involving the careful design and execution of large numbers of precisely controlled measurements, and the statistical analysis and evaluation of the collected data that consumes time and resources. It also requires the use of different data analysis techniques, particularly statistical analysis. Therefore, it is important for personnel who are approaching uncertainty analysis for the determination of repeatability and reproducibility to be aware of the resources required and to carefully lay out a plan for data collection and analysis.

4.1 Problem areas

Some agencies using friction measurement equipment may not have the resources to undertake detailed uncertainty analyses even though, increasingly, quality management standards such as the ISO 9000 series are requiring that all measurement results be accompanied by statements of uncertainty.

4.2 Directions being pursued

Several organizations, such as the National Conference of Standards Laboratories (NCSL) and the International Organization for Standardization (ISO), are investigating methods for dealing with this problem, and there is a document in draft that will recommend a simplified approach to uncertainty analysis based on results of inter-laboratory tests.

4.3 Relationship to inter-agency test results

Many organizations or industries participate in inter-laboratory studies where the test method itself is evaluated:

- Repeatability within organizations
- Reproducibility across organizations

These evaluations do not lead to uncertainty statements because the purpose of the inter-laboratory test is to evaluate, and then improve, the test method as it is applied across the industry. In this particular case the testing, data analysis and harmonization of ground friction measurement equipment will result in an improved self-wet measurement and reporting practice reducing the uncertainty within a measurement device group and across different measurement techniques.

4.4 Default recommendation for organizations

If a testing agency has been party to an inter-organization test that follows the recommendations and analyses of an American Society for Testing Materials standard (ASTM E691) [3] or an ISO standard (ISO 5725) [4], the agency can, as a default, represent its standard uncertainty for a single measurement as the reproducibility standard deviation as defined in ASTM E691 and ISO 5725. This standard deviation includes components for intra-agency repeatability common to all agencies and inter-agency variation. Thus, the organizations participating in the JWRFMP can represent the uncertainty in each individual single runway condition reporting with the reproducibility standard deviation of the respective device that includes components of repeatability standard deviation for the particular device and device family and the reproducibility standard deviation between devices operated by different agencies.

The standard deviation computed in this manner describes a future single measurement made at a laboratory randomly drawn from the group and leads to a prediction interval [5] rather than a confidence interval.

5 UNCERTAINTY ANALYSIS OF THE SAAB FRICTION MEASUREMENT EQUIPMENT

In this study the guidelines of the ASTM E691 and ISO 5725 standards were followed in the data analysis and calculation of the Saab friction measurement device family test method's repeatability and inter-agency reproducibility calculations.

5.1 Procedures in this report

The procedures employed in this study were the standard data analysis procedures in the ASTM E691 and ISO 5725 standards that are intended for test agencies and scientific laboratories that report results of measurements from ongoing or well-documented processes.

For the computational procedures, this study followed the ISO approach [2] to computing and combining components of uncertainty. To this basic structure was added a statistical framework for estimating individual components.

5.1.1 ISO definition of uncertainty

Uncertainty, as defined in the ISO Guide to the Expression of Uncertainty in Measurement [2] and the International Vocabulary of Basic and General Terms in Metrology [6], is a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand."

This definition is consistent with the well-established concept that an uncertainty statement assigns credible limits to the accuracy of a reported value, stating to what extent that value may differ from its reference value [7]. In some cases, reference values are traceable to a national standard and in other cases, reference values are consensus values based on measurements made according to a specific protocol by a group of laboratories. In the case of ground friction measurements in self-wet mode, the latter method is the only acceptable and feasible way.

The uncertainty in the reported measurement value of a friction measurement device is the statistically combined variability of the measurement process with standard deviations for each level of a three-level nested design:

- Level 1 – repeatability (device family-specific statistic representing the ability of the specific device to reproduce the same measurement value under the same circumstances)
- Level 2 – reproducibility (device family-specific statistic representing the ability of different devices of the same type to produce the same measurement result for measurements under the same circumstances)
- Level 3 – stability

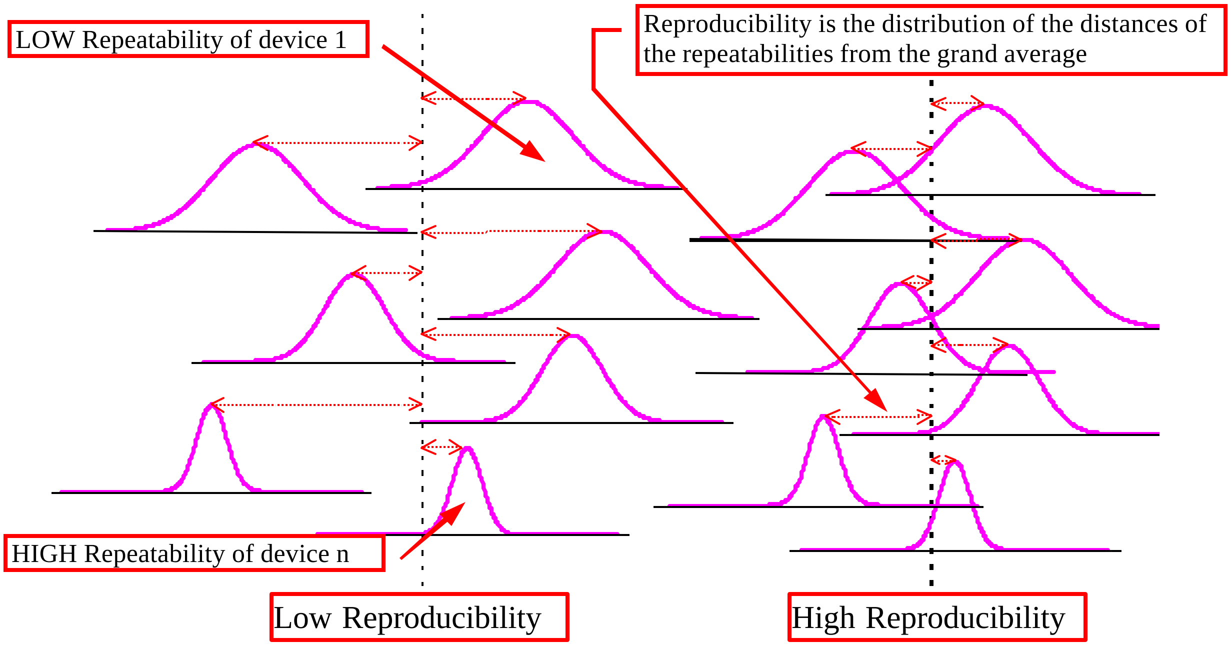


Figure 1. Repeatability and reproducibility

The difference between repeatability and reproducibility can be observed in Figure 1; the two scenarios represent a low and high reproducibility scenario where the individual Gauss curves represent the repeatability statistics for the individual devices. The distribution of the distances from the average centreline of the different Gauss curves represents the reproducibility of the analyzed group of devices. In Figure 1 low and high reproducibility can be observed where the device repeatabilities are identical in magnitude and distribution.

5.2 Analysis of repeatability

Repeatability quantifies the basic precision for a friction measurement device. A Level-1 repeatability standard deviation is computed for each group of J repetitions, and a basic graphical analysis is performed for deciding whether repeatability is dependent on the check standard. Thus, if the Level-1 repeatability of a specific measurement device is depending on the type and friction level of the surface measured throughout the J repeated runs, a time variability graphical analysis is also performed on the data. This second analysis shows whether the repeated runs of the number of measurement devices together with the surface preparatory actions have had any effect on the measured surfaces. Two analysis techniques have been applied to the data for this purpose:

- Check standard plot of Level-1 repeatability standard deviations versus measured surface to show the dependency of variability of measurements on surface friction.
- Lag-plot of measured values per vehicle for time dependency analysis.

Typically, it is expected that the repeatability standard deviation is measuring device dependent – in which case there should be a separate repeatability standard deviation computed for each measurement device. If the measurement devices are all at the same level of precision, the values can be combined over all devices. Since this is not the case for the friction measurement devices, the individual Level-1 repeatability standard deviations have to be calculated and the pooled into the Level-2 reproducibility and stability standard deviations in the data analysis.

Repeatability standard deviations can be pooled over operators, measurement sessions, and surface types. The calculation of the simple repeatability standard deviation from J repetitions is not a reliable estimate of the precision of a specific friction measurement device. Fortunately, these standard deviations can and, according to the ISO and ASTM standards, shall be pooled over measurement sessions and surface types to produce a more reliable precision measure.

The tests done in Prague were designed to produce a nested measurement data structure to provide the underlying database for the calculation of the different levels of repeatability and reproducibility standard deviations and for the mechanism for pooling. The nested design of measurements has three levels:

- J repetitions
- K surfaces
- L measurement sessions

The pooled repeatability standard deviation, calculated from the data of the nested design, has LK(J - 1) degrees of freedom.

5.3 Analysis of reproducibility

Reproducibility quantifies the basic uncertainty and variability of a group of measurement devices that consist of friction measurement devices of the same type or family. A Level-2 reproducibility standard deviation is computed across of the number of participating measurement devices for the L measurement sessions of the K measurement surfaces and pooled across J repetitions.

The Level-2 and Level-3 reproducibility and stability pooled standard deviations were then computed across the measurement sessions and the three different measurement surfaces. Using the three levels of reproducibility standard deviations, the device reproducibility standard deviations were determined for each measurement session and measurement surface.

Characteristically, it is usual for the friction measurement equipment that the reproducibility standard deviation within a group of devices is independent of check standards and measurement speeds. Since the repeatability statistics of the individual devices are dependent on both of these conditions, they cannot be used to factor the reproducibility statistics into device-specific and device family-specific uncertainty.

5.4 Statistical repeatability and reproducibility measures

For a three-level nested design, three basic repeatability statistics of Level-1, Level-2 and Level-3 standard deviations have to be computed across the collected data. The structure of the nested data that has to be set up for the determination of device repeatability is substantially different from the nesting structure of the same data that has to be set up for the calculation of the reproducibility.

In the following paragraphs the computational procedures for the calculation of the three-level standard deviations are given according to the ISO 5725 standard. The explanation of the data structure and the methods of pooling the different levels of standard deviations are given in the respective section for the repeatability and reproducibility analysis.

The measurements from the nested design are denoted by:

$$m_{lkj} \quad \left(l = 1 \ldots L, k = 1 \ldots K, j = 1 \ldots J\right) \tag{1}$$

Equations corresponding to three-level nested data analysis are shown below. Level-1 repeatability standard deviations are pooled over K surfaces and L measurement sessions. Individual standard deviations with (J - 1) degrees of freedom each are computed from J repetitions as

$$s_1 = \sqrt{\frac{1}{J-1}\sum_{j=1}^{J}\left(m_{lkj} - \overline{m}_{lk\bullet}\right)^2} \tag{2}$$

where

$$\overline{m}_{lk\bullet} = \frac{1}{J}\sum_{j=1}^{J} m_{lkj} \tag{3}$$

Level-2 standard deviations are pooled over L measurement sessions where individual standard deviations with (K - 1) degrees of freedom each are computed from K surface averages as

$$s_2 = \sqrt{\frac{1}{K-1}\sum_{k=1}^{K}\left(\overline{m}_{lk\bullet} - \overline{m}_{l\bullet\bullet}\right)^2} \tag{4}$$

where

$$\overline{m}_{l\bullet\bullet} = \frac{1}{K}\sum_{k=1}^{K} \overline{m}_{lk\bullet} \tag{5}$$

A Level-3 standard deviation with (L - 1) degrees of freedom is computed from L measurement session averages as

$$s_3 = \sqrt{\frac{1}{L-1}\sum_{l=1}^{L}\left(\overline{m}_{l\bullet\bullet} - \overline{m}_{\bullet\bullet\bullet}\right)^2} \tag{6}$$

where

$$\overline{m}_{\bullet\bullet\bullet} = \frac{1}{L}\sum_{l=1}^{L} \overline{m}_{l\bullet\bullet} \tag{7}$$

The standard deviation that defines the uncertainty for a single measurement on a test-specific test surface by a particular device is given by

$$s_R = \sqrt{s_{surfaces}^2 + s_{Measurement\ Sessions}^2 + s_1^2} = \sqrt{s_3^2 + \frac{K-1}{K} \cdot s_2^2 + \frac{J-1}{J} \cdot s_1^2} \qquad (8)$$

The different pooled standard deviation components represent uncertainty mechanisms that have to be pooled for the device-specific repeatability standard deviations and the measuring equipment type specific reproducibility standard deviations can be computed individually as

$$s_{Measurement\ Session} = \sqrt{s_3^2 - \frac{1}{K} \cdot s_2^2} \qquad (9)$$

$$s_{Surfaces} = \sqrt{s_2^2 - \frac{1}{J} \cdot s_1^2} \qquad (10)$$

5.5 Revision of theory for the actual test conditions

During the Prague measurement session of the JWRFMP there was only one test area available. The surface measured was on the south end of Runway 04/22 of the PRAHA/Ruzene Airport left of the centreline in line with the touchdown paint-marks. The surface was divided into three test sections:

A	section of bare asphalt, 100 m long
PAINT	the paint section that was defined to fall onto the touchdown paint-marks, 60 m long
C	third section of bare asphalt, 100 m long

The following runs were made on these three test sections:

- 10 repeated runs with “AS IS” condition at 65 km/h
- 10 repeated runs with “AS IS” condition at 95 km/h
- 10 repeated runs with “AS IS” condition and 30 psi tire pressure at 65 km/h
- 10 repeated calibrated runs with ASTM E1551 tires (100 psi) at 65 km/h
- 10 repeated calibrated runs with ASTM E1551 tires (100 psi) at 95 km/h

5.5.1 Modification of statistical calculations for the repeatability standard deviation computation

Based on these measurements, considering the constraints inherent in the measured data, the presented uncertainty analysis has to be adapted with a modified nested design and a new pooling of the Level-2 standard deviations to adapt to the available data. The Level-1 repeatability standard deviations with (J - 1) degrees of freedom each are computed from J repetitions with equations (2) and (3), where J = 10, because in each test 10 repeated runs were made. This shows the Level-1 repeatability standard deviation of each device on each test surface for each measuring run.

According to equations (4) and (5), the Level-2 repeatability standard deviation could be calculated for each of the three test sections – test section A, test section PAINT and test section C – pooled over the five different measuring runs. This would provide a better indication of the sensitivity of each device for the different measuring setup – speed, tire pressure, etc. – than the repeatability for the different measuring setup. Our objective was to get an indication for each device's repeatability pooled over different measuring sessions and test setup independent of the sensitivity of the devices to the measuring setup.

Therefore, we developed a new Level-2 standard deviation where all standard deviations from the Level-1 standard deviations were pooled together. This shows the standard deviation of a device that is independent of measurement runs. This technique (pooling standard deviations from different check standards) allows computing a more meaningful uncertainty measure. Equation (11) reflects the device uncertainty affected by repeat runs and measuring runs.

$$^{5}\Gamma_{A}^{2} = \sqrt{\frac{N_a \cdot s_{A_a}^{2} + N_b \cdot s_{A_b}^{2} + N_c \cdot s_{A_c}^{2} + N_d \cdot s_{A_d}^{2} + N_e \cdot s_{A_e}^{2}}{N_a + N_b + N_c + N_d + N_e}} \tag{11}$$

$$^{5}\Gamma_{PAINT}^{2} = \sqrt{\frac{N_a \cdot s_{PAINT_a}^{2} + N_b \cdot s_{PAINT_b}^{2} + N_c \cdot s_{PAINT_c}^{2} + N_d \cdot s_{PAINT_d}^{2} + N_e \cdot s_{PAINT_e}^{2}}{N_a + N_b + N_c + N_d + N_e}} \tag{12}$$

$$^{5}\Gamma_{C}^{2} = \sqrt{\frac{N_a \cdot s_{C_a}^{2} + N_b \cdot s_{C_b}^{2} + N_c \cdot s_{C_c}^{2} + N_d \cdot s_{C_d}^{2} + N_e \cdot s_{C_e}^{2}}{N_a + N_b + N_c + N_d + N_e}} \tag{13}$$

where

$^{5}G^{2}{}_{\mathrm{A}}$ is the Level-2 repeatability standard deviation for section A with 5 degrees of freedom,

$^{5}G^{2}{}_{\mathrm{PAINT}}$ is the Level-2 repeatability standard deviation for section PAINT with 5 degrees of freedom, and

$^{5}G^{2}{}_{\mathrm{C}}$ is the Level-2 repeatability standard deviation for section C with 5 degrees of freedom.

According to equations (6) and (7) the Level-3 repeatability standard deviation would be the repeatability standard deviation of the average friction of the different test sections: test section A, test section PAINT and test section C. Because we had different friction levels on each test section, the standard deviation of these would just show how different the surfaces were and would not depend on the device. Therefore, by using the above calculated new Level-2 standard deviations, we were able to pool together a new Level-3 standard deviation where all standard deviations from different friction levels and different measurement runs were pooled together. This shows the standard deviation of a device that is independent from friction level and independent of measurement runs. Equation (14) reflects the device uncertainty affected by repeat runs, time variations and different friction levels.

This Level-3 standard deviation is calculated using the following equation:

$$s_3 = \sqrt{\frac{5\cdot{}^5\Gamma_A^2 + 5\cdot{}^5\Gamma_{PAINT}^2 + 5\cdot{}^5\Gamma_C^2}{5+5+5}} \qquad (14)$$

where ${}^5\Gamma_A{}^2$, ${}^5\Gamma_{PAINT}{}^2$, ${}^5\Gamma_C{}^2$ are defined in equations (11) through (13).

5.5.2 Modification of the statistical calculations for the reproducibility standard deviation computation

The calculation of the Level-1 reproducibility standard deviation is based on equations (1) and (2) and it is calculated for each repeated run of the different measuring runs pooled over the seven different measuring devices.

The calculation of the Level-2 reproducibility standard deviation is based on equations (4) and (5) and it is calculated for the different measuring runs pooled over the ten repeated runs.

According to equations (6) and (7), the Level-3 reproducibility standard deviation could be calculated for each of the three test sections – test section A, test section PAINT and test section C – pooled over the five different measuring runs. This would indicate the sensitivity of the devices for the different measuring setups – speed, tire pressure, etc. – rather than the reproducibility of the different measuring setup. Our objective was to get an indication for the reproducibility pooled over different measuring setups that is independent of the nominal variations of the devices for these different setups. Therefore, using the technique used for the repeatability calculation, we get a new Level-3 reproducibility standard deviation where all standard deviations from the Level-1 reproducibility standard deviations were pooled together. This shows the reproducibility standard deviation of a device group that is independent of friction levels and measurement runs.

This Level-3 reproducibility standard deviation was calculated for each of the three test sections – test section A, test section PAINT and test section C – using the following equations:

$$s_{3A} = \sqrt{\frac{10\cdot{}^{10}\Gamma_{A1}^2 + 10\cdot{}^{10}\Gamma_{A2}^2 + \cdots + 10\cdot{}^{10}\Gamma_{A5}^2}{10+10+10+10+10}} \qquad (15)$$

where

$${}^{10}\Gamma_{AI}^2 = \sqrt{\frac{N_1 \cdot s_{AI_1}^2 + N_2 \cdot s_{AI_2}^2 + \ldots\ldots + N_9 \cdot s_{AI_{10}}^2 + N_{10} \cdot s_{AI_{10}}^2}{N_1 + N_2 + \ldots. + N_9 + N_{10}}} \qquad (16)$$

I = 1,2,3,4,5 for the 5 different measurement runs.

$$s_{3PAINT} = \sqrt{\frac{10 \cdot {}^{10}\Gamma^2_{PAINT1} + 10 \cdot {}^{10}\Gamma^2_{PAINT2} + \cdots + 10 \cdot {}^{10}\Gamma^2_{PAINT5}}{10 + 10 + 10 + 10 + 10}} \tag{17}$$

where

$${}^{10}\Gamma^2_{PAINTI} = \sqrt{\frac{N_1 \cdot s^{\,2}_{PAINTI_1} + N_2 \cdot s^{\,2}_{PAINTI_2} + \ldots\ldots + N_9 \cdot s^{\,2}_{PAINTI_{10}} + N_{10} \cdot s^{\,2}_{PAINTI_{10}}}{N_1 + N_2 + \ldots . + N_9 + N_{10}}} \tag{18}$$

I = 1,2,3,4,5 for the 5 different measurement runs.

$$s_{3C} = \sqrt{\frac{10 \cdot {}^{10}\Gamma^2_{C1} + 10 \cdot {}^{10}\Gamma^2_{C2} + \cdots + 10 \cdot {}^{10}\Gamma^2_{C5}}{10 + 10 + 10 + 10 + 10}} \tag{19}$$

where

$${}^{10}\Gamma^2_{CI} = \sqrt{\frac{N_1 \cdot s^{\,2}_{CI_1} + N_2 \cdot s^{\,2}_{CI_2} + \ldots\ldots + N_9 \cdot s^{\,2}_{CI_{10}} + N_{10} \cdot s^{\,2}_{CI_{10}}}{N_1 + N_2 + \ldots . + N_9 + N_{10}}} \tag{20}$$

I = 1,2,3,4,5 for the 5 different measurement runs.

5.6 Assumptions

The measurement of friction coefficient is a physical phenomenon where the reference values must be consensus-based values in the absence of any traceable physical or international standard, where the reference is based on measurements made according to a specific protocol by a group of laboratories. This specific protocol was not available at the time of the preparation of this report and therefore, with no calibration reference available, bias could not be established for the analyzed friction measurement devices. The research and development work performed by the many contributors throughout the JWRFMP has produced a standard and reference device under development. The International Reference Vehicle (IRV) participated in the Prague testing but, due to technical problems, was not able to provide sufficient number and quality measurements to be used as a base reference.

For a friction measurement device, any repeatability measurements will include some variance stemming from surface texture and surface material. This surface variance comes from the fact that the surface is not manufactured completely uniform and is subjected to wear from use and/or weathering. Also, although every care has been taken to mark the measurement lanes both in lateral and longitudinal positions, the devices at every run measure slightly different wheel tracks, dependent on driver skill.

No attempt has been made to separate the surface variance from the device variance, as there is no method or standardized procedure available.

Within the JWRFMP, harmonization and reproducibility are addressed in several reports. Other relevant work to this report on these topics can be found in [8] and [9].

6 FIELD TESTS

6.1 Field test data

The participants of the friction measurement tests completed at Prague Airport in March 2002 provided the database for this study. These tests were conducted within the framework of the JWRFMP.

The compiled database of the different test sessions and runs from the Prague testing comprises measurements from 12 different friction measurement devices operated in self-wet mode as listed in Table 1.

Table 1. Participating friction measurement devices

Device Description	Tire Type	Device code
IRFI-Int'l Reference Vehicle (IRV)	PIARC Smooth Treaded Tire	IMAG-IRV-PIARC-22
ASFT801	ASTM E-1551 (100 psi)	ASFT-801-E1551-100
	Unitester 520 tire (100 psi)	ASFT-801-AERO-100
	Unitester 520 tire (30 psi)	ASFT-801-AERO-30
ASFT810	ASTM E-1551 (100 psi)	ASFT-810-E1551-100
	Unitester 520 tire (100 psi)	ASFT-810-AERO-100
	Unitester 520 tire (30 psi)	ASFT-810-AERO-30
Vienna airport BV-11 (no self watering system)	Trelleborg 520	BV11-VIE-T520-100
Düsseldorf Airport SFT (Sarsys)	ASTM E-1551 (100 psi)	SAR-813-E1551-100
	Unitester 520 tire (100 psi)	SAR-813-AERO-100
	Unitester 520 tire (30 psi)	SAR-813-AERO-30
Munich Airport SFT (Sarsys)	ASTM E-1551 (100 psi)	SAR-602-E1551-100
	Unitester 520 tire (100 psi)	SAR-602-AERO-100
	Unitester 520 tire (30 psi)	SAR-602-AERO-30
Frankfurt Airport SFT (Sarsys)	ASTM E-1551 (100 psi)	SAR-527-E1551-100
	Unitester 520 tire (100 psi)	SAR-527-AERO-100
	Unitester 520 tire (30 psi)	SAR-527-AERO-30
Prague Airport SFT79 (Safegate)	ASTM E-1551 (100 psi)	SFT-511-E1551-100
	Unitester 520 tire (100 psi)	SFT-511-AERO-100
	Unitester 520 tire (30 psi)	SFT-511-AERO-30
FAA-SFT	ASTM E-1551 (100 psi)	SFT-212-E1551-100
	ASTM E-1551 (30 psi)	SFT-212-E1551-30
Arlanda Airport SFT (Sarsys)	ASTM E-1551 (100 psi)	SAR-805-E1551-100
	Unitester 520 tire (100 psi)	SAR-805-AERO-100
	Unitester 520 tire (30 psi)	SAR-805-AERO-30
Strate Hydro- SFT (Sarsys)	ASTM E-1551 (100 psi)	SAR-814-E1551-100
	ASTM E-1551 (30 psi)	SAR-814-E1551-30
TATRA 613 (no self watering system)	ASTM- E1551 (100 psi)	TATRA-613-E1551-100

Figure 2. Participating devices

The original scope of the test was to conduct measurements on numerous different surfaces, mainly winter surfaces, but due to mild weather it was not possible. Accordingly, the measurements analyzed in this report were made on a limited selection of surfaces.

During this measurement session of the JWRFMP there was only one test area available. The surface measured was on the south end of Runway 04/22 of the PRAHA/Ruzene Airport left of the centre lane in line with the touchdown paint-marks. The surface was divided into three test sections:

A	section of bare asphalt, 100 m long
PAINT	the paint section that was defined to fall onto the touchdown paint-marks, 60 m long
C	third section of bare asphalt, 100 m long

The measurement direction used throughout the tests was always the same, runway direction 22 (220°).

The PAINT section was shorter than the optimal desirable section length for repeatability and reproducibility measurements. Therefore, the results from this section were treated with extreme caution and particular care to eliminate the effect of the shorter-than-optimal length.

Figure 3. Test sections

Figure 4. Overall view of touchdown paint marker

6.2 Field test procedures

Each device conducted 10 repeat runs within each test. The devices were following a pre-determined sequence in following one another for each project. Thus, during the measurement project planning, a device sequence was developed and the supervisors on the measurement field ensured the run sequences were followed. This provided a well-organized testing scheme. The devices were following one another, observing safe distances throughout the test section, returning to the start point on the other side of runway and waiting for the last measurement car of the sequence to finish its run and reach the start point before beginning the next run sequence. The run sequences are referred to as waves. Thus one run of every vehicle within a test project was considered as a wave. (See detailed number of runs in Table 2 and Table 3)

Table 2. List of test sessions and device runs

Project No	Test No	Date	ASFT 801	ASFT810	FAA-SFT	SFT-PRA	IRV	DU-SFT
1101	02.64.01	5-Mar-02	10	10	10	8	10	10
1102	02.64.02	5-Mar-02	10	10	10	10		10
1103	02.65.01	6-Mar-02	10	10	10	10		
1104	02.65.02	6-Mar-02	10	10	10	10		
1105	02.65.03	6-Mar-02	10	10	10	10	10	
Number of runs			**50**	**50**	**50**	**48**	**20**	**20**

Table 3. List of test sessions and device runs (cont.)

Project No	FRA-SFT	SFT-ARL	STR-SFT	BV11-VIEN	TATRA	Total runs	Total section runs
1101	10	10	10	10	10	**58**	174
1102	10	10	9	10	8	**50**	150
1103	10	10	10	10		**40**	120
1104	10	10	10	10		**40**	120
1105	10	10	10	10		**50**	150
Number of runs	**50**	**50**	**49**	**50**	**18**	**238**	**714**

The testing was conducted with the breakdown of the measurements into projects. Each project was identified with its project number, date and time. The projects were planned and documented prior to testing. Each project was designed for a specific purpose throughout the tests. The projects were composed of a number of waves of measurements with different devices. Within a project and in-between the measurement waves, surface conditioning was scheduled in the planning and executed throughout the measurements. The number of devices in self-wet mode raised the concern that the surface drainage and water evaporation was not sufficient from one wave to the next for the water deposited on the measurement surface to diminish. Thus, the accumulated water depth for many repeated waves would effect the measurements. For this purpose a runway sweeper and blower was employed throughout the testing. For the different projects the blower was operated with the sweeper brush and air blower on the surface in-between waves according to the project plan.

The following test projects were completed:

- **Project No: 1101, Test Number: 02.64.01**

  Base line measurement with 'AS IS' condition

  All participating measurement vehicles prior to the measurement project were calibrated according to their respective standard calibration procedure. The measuring devices were using their standard measurement tires with standard nominal inflation pressure to represent the measurement vehicle's normal operating conditions and procedures. The test speed was 65 km/h and each device used its own self-wet system except for the BV11 and the TATRA measuring devices. These devices did not have their own self-wet equipment at the testing to provide the 1 mm water depth required by International Civil Aviation Organization. To accommodate for the need of a wet surface, these two devices were scheduled at the end of each wave to be able to run in the already dispensed water path of the previous devices of the wave. Before each the project's 10 repeated and recorded measurement waves began, each measuring device made a surface and tire preparation run. The run was conducted with no self-watering applied on a separate path of the runway surface. The run served several purposes: preparation of the measurement tire, equipment functionality check, and calibration checks. The water was swept and blown away from the surface after every second wave.

  The devices listed in Table 4 participated in this test in the same order as they are listed in the table.

Table 4. Devices participating in project No. 1101

Order No	Device	Tire	Tire Pressure/ Tread Depth	Tire Batch No/SN	DeviceTireConfigID
1	ASFT801	Unitester 520	100 psi/ 8 mm	3901/801-1	ASFT-801-UNIT-100
2	ASFT810	Unitester 520	100 psi/ 8 mm	3901/810-2	ASFT-810-UNIT-100
3	FAA-SFT	ASTM E1551	100 psi/ 3 mm	8/53-969	SFT-212-E1551-100
4	SFT-PRA	Unitester 520	100 psi/ unknown	3900/unknown	SFT-511-UNIT-100
5	IRV	PIARC smooth	100 psi/ unknown	Unknown	IMAG-IRV-PIARC-22
6	DUS-SFT	Unitester 520	100 psi/ unknown	2201/unknown	SAR-813-UNIT-100
7	FRK-SFT	Unitester 520	100 psi/ 6 mm	2001/3655-1	SAR-527-UNIT-100
8	SFT-ARL	Unitester 520	100 psi/ unknown	3901/unknown	SAR-805-UNIT-100
9	STR-SFT	ASTM E1551	30 psi/ unknown	4/unknown	SAR-814-E1551-30
10	BV11-VIEN	Trelleborg T520	100 psi/ unknown	Unknown	BV11-VIE-T520-100
11	TATRA	ASTM E1551	100 psi/ unknown	Unknown	TATRA-613-E1551-100

Figure 5. Calibration for devices

- **Project No: 1102, Test Number: 02.64.02**

Base line measurement with 'AS IS' condition

Within this test project the target test speed was 95 km/h and each device used its own self-wet system except the BV11 and the TATRA. These devices again were scheduled to run as the last two devices of each wave in the water path of the other devices. Before the 10 repeated runs, each device made a surface and tire preparation run. The water was swept and blown away from the surface after every second wave.

The devices listed in Table 5 participated in this test in the same order as they are listed in the table.

Table 5. Devices participating in project No. 1102

Order No	Device	Tire	Tire Pressure/ Tread Depth	Tire Batch No/SN	DeviceTireConfigID
1	ASFT801	Unitester 520	100 psi/ 8 mm	3901/801-1	ASFT-801-UNIT-100
2	ASFT810	Unitester 520	100 psi/ 8 mm	3901/810-2	ASFT-810-UNIT-100
3	FAA-SFT	ASTM E1551	100 psi/ 3 mm	8/53-969	SFT-212-E1551-100
4	SFT-PRA	Unitester 520	100 psi/ unknown	3900/unknown	SFT-511-UNIT-100
5	DUS-SFT	Unitester 520	100 psi/ unknown	2201/unknown	SAR-813-UNIT-100
6	FRK-SFT	Unitester 520	100 psi/ 6 mm	2001/3655-1	SAR-527-UNIT-100
7	SFT-ARL	Unitester 520	100 psi/ unknown	3901/unknown	SAR-805-UNIT-100
8	STR-SFT	ASTM E1551	100 psi/ unknown	4/unknown	SAR-814-E1551-100
9	TATRA	ASTM E1551	100 psi/ unknown	Unknown	TATRA-613-E1551-100
10	BV11-VIEN	Trelleborg T520	100 psi/ unknown	Unknown	BV11-VIE-T520-100

- **Project No: 1103, Test Number: 02.65.01**

Base line measurement with 'AS IS' condition

All the vehicles were calibrated according to their standard procedure and all devices were using their standard tires, but with 30 psi inflation pressure. The test speed was 65 km/h and each device used its own self-wet system except the BV11 and the TATRA, which ran at the end of each wave in the water path of the other devices. Before the 10 repeated runs, each device made a surface and tire preparation run. The water was swept and blown away from the surface after every second wave.

The devices listed in Table 6 participated in this test in the same order as they are listed in the table.

Table 6. Devices participating in project No. 1103

Order No	Device	Tire	Tire Pressure/ Tread Depth	Tire Batch No/SN	DeviceTireConfigID
1	ASFT801	Unitester 520	30 psi/ 8 mm	3901/801-1	ASFT-801-UNIT-30
2	ASFT810	Unitester 520	30 psi/ 8 mm	3901/810-2	ASFT-810-UNIT-30
3	FAA-SFT	ASTM E1551	30 psi/ 3 mm	8/53-969	SFT-212-E1551-30

4	SFT-PRA	Unitester 520	30 psi/ unknown	3900/unknown	SFT-511-UNIT-30
5	DUS-SFT	Unitester 520	30 psi/ unknown	2201/unknown	SAR-813-UNIT-30
6	FRK-SFT	Unitester 520	30 psi/ 6 mm	2001/3655-1	SAR-527-UNIT-30
7	SFT-ARL	Unitester 520	30 psi/ unknown	3901/unknown	SAR-805-UNIT-30
8	STR-SFT	ASTM E1551	30 psi/ unknown	4/unknown	SAR-814-E1551-30
9	BV11-VIEN	Trelleborg T520	30 psi/ unknown	Unknown	BV11-VIE-T520-30

Figure 6. "AS IS" run of every vehicle

After the base line measurements, the participating measurement devices underwent the following procedures:

- The measuring tire of each device was changed to the ASTM E1551 (100 psi) standard measurement tire.
- One designated calibration crew has calibrated each of the equipments with one special calibration device. With this procedure the error sources that might come from the differences in the various calibration equipment and the procedures followed by the different operators were minimized.

Figure 7. Changing tires to ASTM E1551

- **Project No: 1104, Test Number: 02.65.02**

Calibrated measurement with ASTM E1551 tires (100 psi)

The test speed was set at 65 km/h and each device used its own self-wet system except the BV11 and the TATRA, which ran at the end of each wave in the water path of the other devices. Before the 10 repeated runs, each device made a surface and tire preparation run. The water was swept and blown away from the surface after every second wave.

The devices listed in Table 7 participated in this test in the same order as they are listed in the table.

Table 7. Devices participating in project No. 1104

Order No	Device	Tire	Tire Pressure/ Tread Depth	Tire Batch No/SN	DeviceTireConfigID
1	ASFT801	ASTM E1551	100 psi/ 8 mm	Unknown	ASFT-801-E1551-100
2	ASFT810	ASTM E1551	100 psi/ 8 mm	Unknown	ASFT-810- E1551-100
3	FAA-SFT	ASTM E1551	100 psi/ 3 mm	Unknown	SFT-212-E1551-100

4	SFT-PRA	ASTM E1551	100 psi/ 8 mm	Unknown	SFT-511-E1551-100
5	DUS-SFT	ASTM E1551	100 psi/ 8 mm	Unknown	SAR-813-E1551-100
6	FRK-SFT	ASTM E1551	100 psi/ 6 mm	Unknown	SAR-527-E1551-100
7	SFT-ARL	ASTM E1551	100 psi/ 8 mm	Unknown	SAR-805-E1551-100
8	STR-SFT	ASTM E1551	100 psi/ 8 mm	Unknown	SAR-814-E1551-100
9	BV11-VIEN	Trelleborg T520	100 psi/ unknown	Unknown	BV11-VIE-T520-100

Figure 8. Calibration

- **Project No: 1105, Test Number: 02.65.03**

Calibrated measurement with ASTM E1551 tires (100 psi)

The test speed was 95 km/h and each device used its own self-wet system except the BV11 and the TATRA, which ran at the end of each run in the water path of the other devices. Before the 10 repeated runs, each device made a surface and tire preparation run. The water was swept and blown away from the surface after every second wave.

The devices listed in Table 8 participated in this test in the same order as they are listed in the table.

Table 8. Devices participating in project No. 1105

Order No	Device	Tire	Tire Pressure/ Tread Depth	Tire Batch No/SN	DeviceTireConfigID
1	ASFT801	ASTM E1551	100 psi/ 8 mm	Unknown	ASFT-801-E1551-100
2	ASFT810	ASTM E1551	100 psi/ 8 mm	Unknown	ASFT-810- E1551-100
3	FAA-SFT	ASTM E1551	100 psi/ 3 mm	Unknown	SFT-212-E1551-100
4	SFT-PRA	ASTM E1551	100 psi/ 8 mm	Unknown	SFT-511-E1551-100
5	DUS-SFT	ASTM E1551	100 psi/ 8 mm	Unknown	SAR-813-E1551-100
6	FRK-SFT	ASTM E1551	100 psi/ 6 mm	Unknown	SAR-527-E1551-100
7	SFT-ARL	ASTM E1551	100 psi/ 8 mm	Unknown	SAR-805-E1551-100
8	STR-SFT	ASTM E1551	100 psi/ 8 mm	Unknown	SAR-814-E1551-100
9	BV11-VIEN	Trelleborg T520	100 psi/ unknown	Unknown	BV11-VIE-T520-100

7 DATA AND ANALYSIS

In this section the results of the data analysis are presented. The first step of the statistical analysis was detecting the outliers in the data sets. In addition to the ASTM E691 and ISO 5725 standard uncertainty measures of the three different levels of repeatability, reproducibility and stability measures, the “Coefficient of Variation” and “Standard Error of Measurements” statistical parameters were also calculated and reported. These additional measures ensured the compatibility and comparability of the test results to the variability studies that have been performed for various other devices in the past.

7.1 Identifying the outliers

The Grubbs' test was used to detect outliers in our data set. It is based on the assumption of normality: the data set can be reasonably approximated by a normal distribution. The Grubbs' test detects one outlier at a time. This outlier is expunged from the data set and the test is iterated until no outliers are detected. It is also known as the maximum normed residual test.

The Grubbs' test statistic is defined as

$$G = \frac{\max\left|Y_i - \overline{Y}\right|}{s} \tag{21}$$

where $\overline{Y}$ and s are the sample mean and standard deviation. The Grubbs' test statistic is the largest absolute deviation from the sample mean in units of the sample standard deviation.

The hypothesis of no outliers is rejected if

$$G > \frac{(N-1)}{\sqrt{N}} \cdot \sqrt{\frac{t^2_{(a/(2N),N-2)}}{N-2+t^2_{(a/(2N),N-2)}}} \tag{22}$$

where $t^2_{(a/(2N),N-2)}$ is the critical value of the t-distribution with (N-2) degrees of freedom and a significance level of $\alpha/(2N)$.

In the above formulas for the critical regions, [1] follows the convention that is the upper critical value from the t-distribution and is the lower critical value from the t-distribution.

Applying the above formulas the outliers were identified. The complete data set with the indication of the outliers can be found in the Appendix A.

7.2 Repeatability statistics

The following data analysis steps were demonstrated for each of the Saab friction measurement devices that performed enough measurement runs throughout the testing to provide data sufficient for uncertainty analysis:

1. ***Lag Plot*** for the tests done before and after the unified and standard calibration. The lag plot is a tool used in the ISO standard to discover tendencies in the data that would indicate the dependency of the data on a physical phenomenon or time throughout the measurement. The lag plot is a simple plot of the data measured by a device as a function of the previous measurement of the same device. The data points should appear in a cloud pattern without trends. An observable trend would indicate a measurement dependency.
2. ***Check Standard Plot*** for the measurement device. The check standard graph is a tool used for discovering whether the uncertainty of a measurement device is dependent on the nominal value of the measurement. The graph is a plot of the calculated simple standard deviation of the repeated measurement runs against the average of the measured data for the corresponding number of repeat measurements.

3. ***Repeatability Plot*** for the measurement device. The repeatability plot is the plot of the pooled Level-2 repeatability standard deviations of the device for the different surfaces with base as the average measurement value. This graph is a standard bar chart containing the average of the repeated measurement runs for the different sessions on the different surfaces with different speeds. The repeatability standard deviation is plotted on the corresponding bars as a standard error bar.
4. ***Coefficient of Variation Plot*** for the measurement device. The coefficient of measurement plot depicts the calculated coefficient of variation statistics for a device in one graph for the different surfaces and measurement target speeds grouped for the different measurement sessions.
5. ***Standard Error Plot*** for the measurement device. The standard error plot depicts the calculated standard error statistics for a device in one graph for the different surfaces and measurement target speeds grouped for the different measurement sessions.

These six different plots were produced for eight of the ten participating measurement devices and are shown in Figure 9 through Figure 56. Data point symbols are used to identify speed and surface parameters. Devices SAR-813 and SAR-602 did not complete a sufficient number of test runs to be included in this uncertainty statistical analysis.

7.2.1 ASFT-801

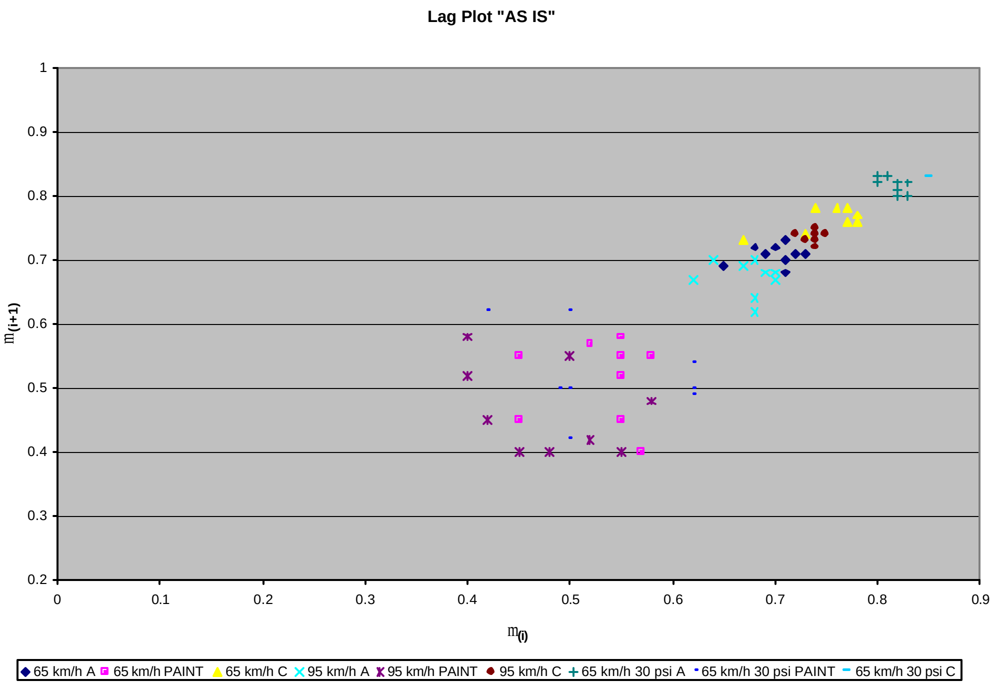


Figure 9. Lag plot for ASFT-801 before uniform calibration

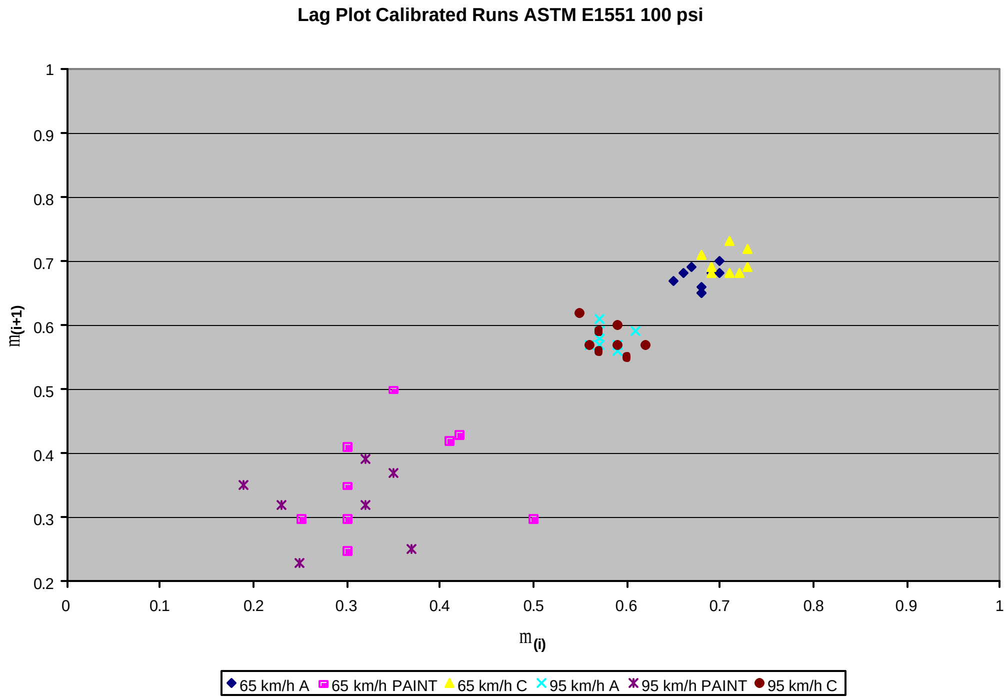


Figure 10. Lag plot for ASFT-801 after uniform calibration

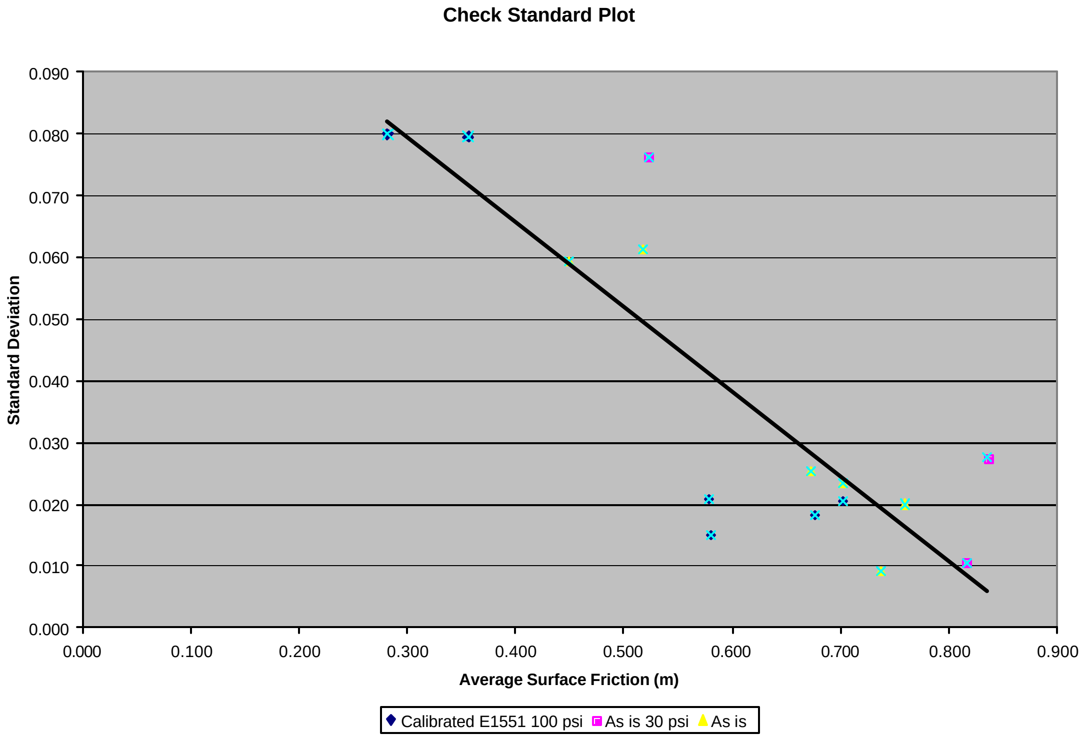


Figure 11. Check standard plot for ASFT-801

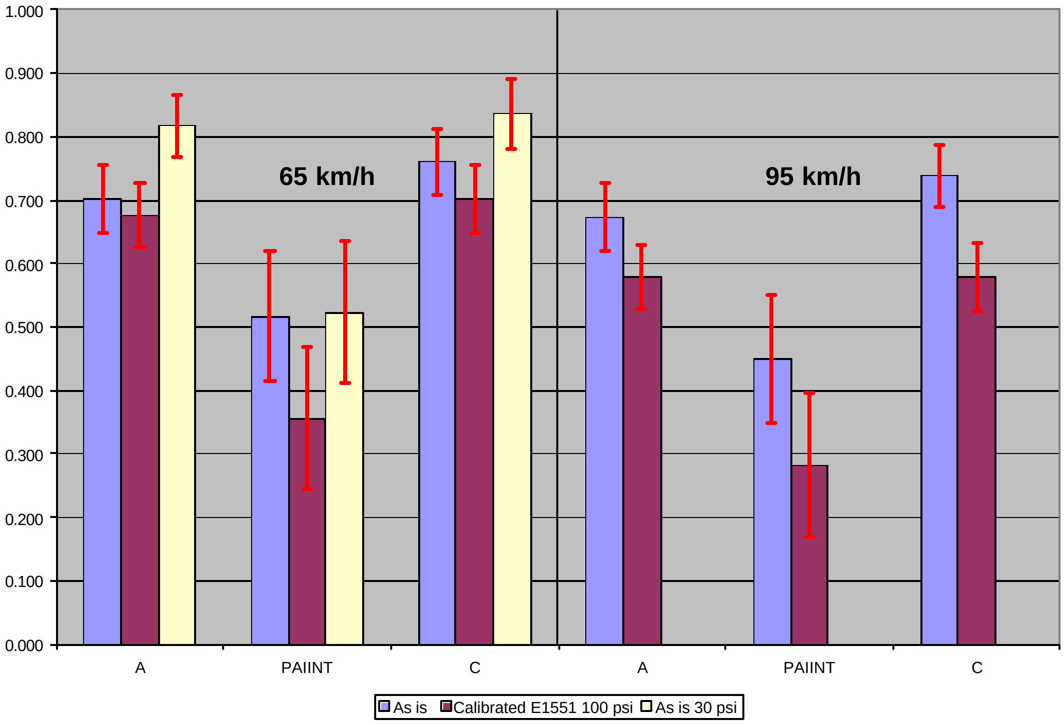


Figure 12. Repeatability plot for ASFT-801

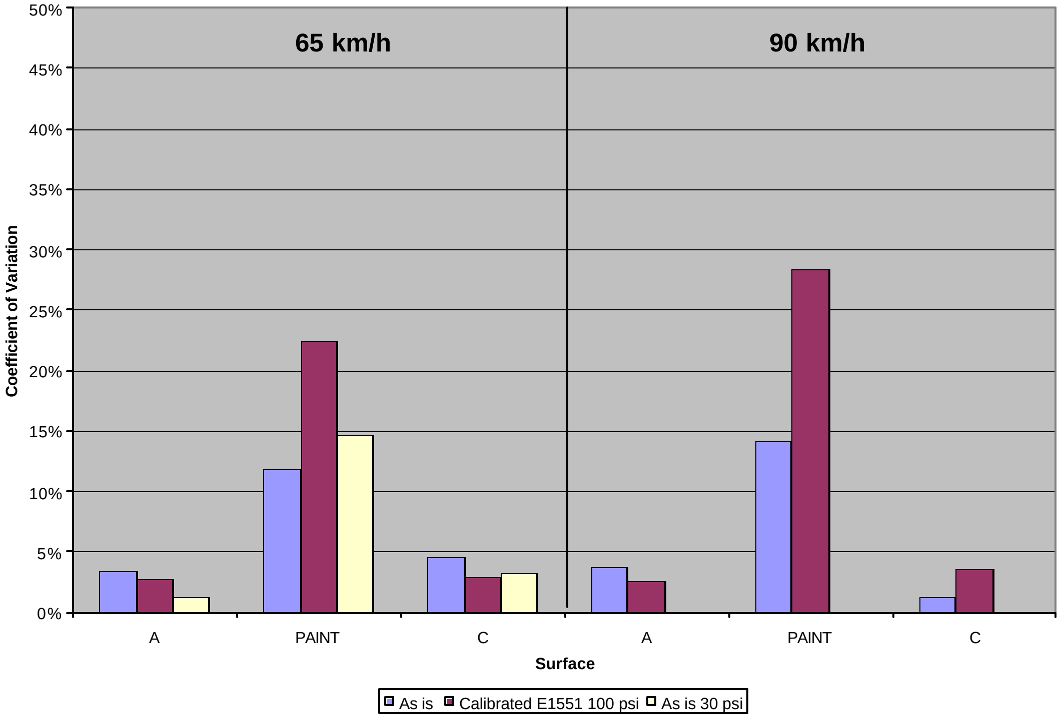


Figure 13. Coefficient of variation plot for ASFT-801

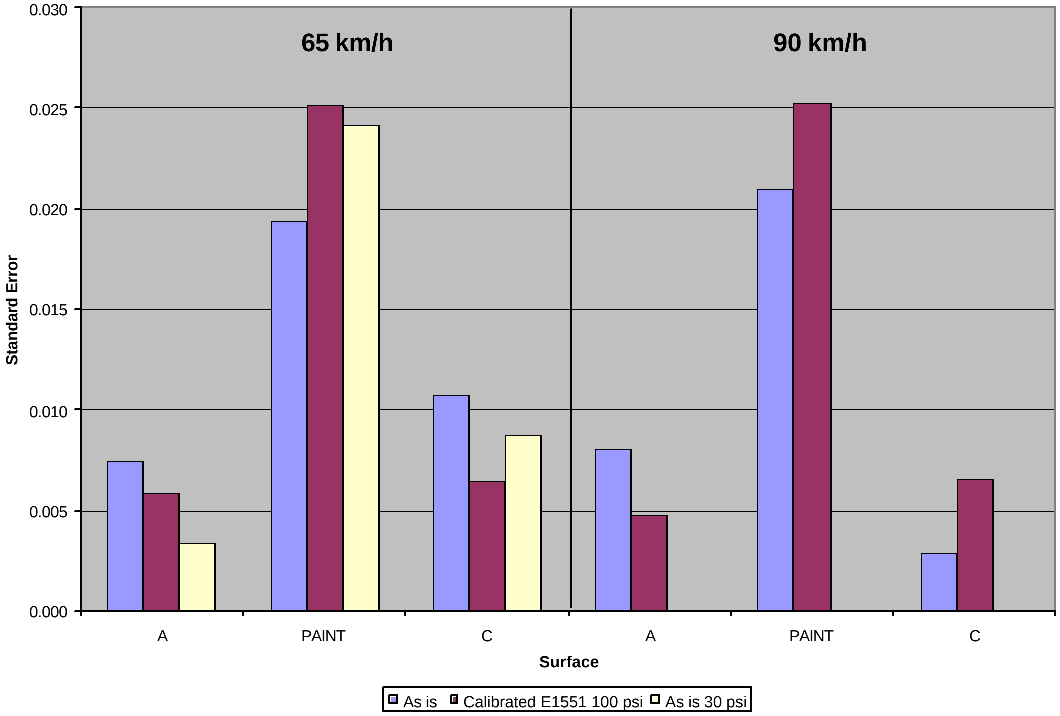


Figure 14. Standard Error plot for ASFT-801

7.2.2 ASFT-810

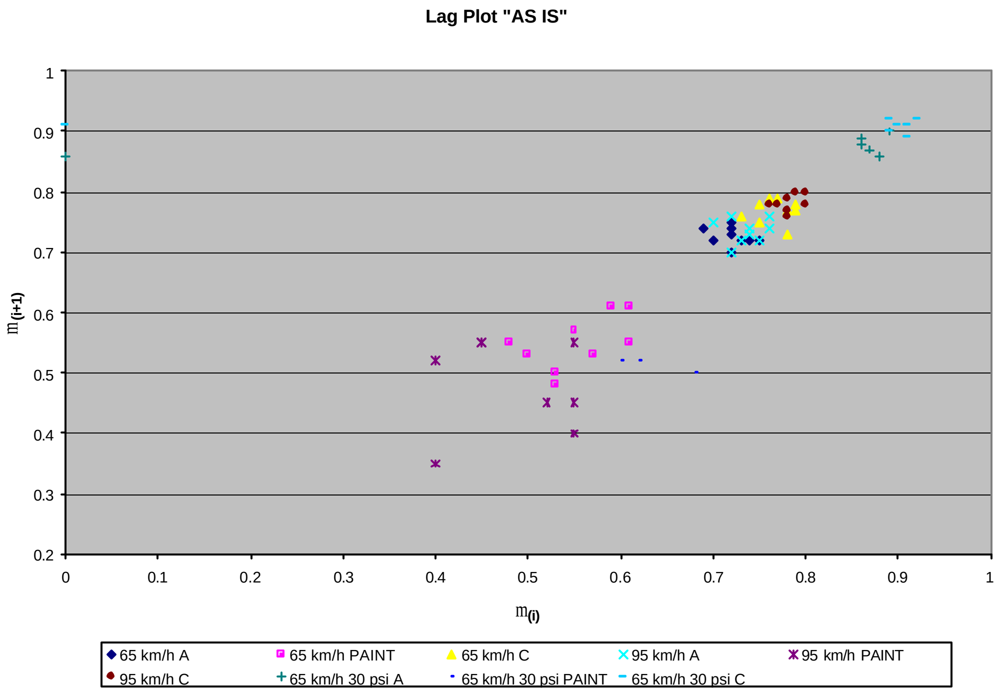


Figure 15. Lag plot for ASFT-810 before uniform calibration

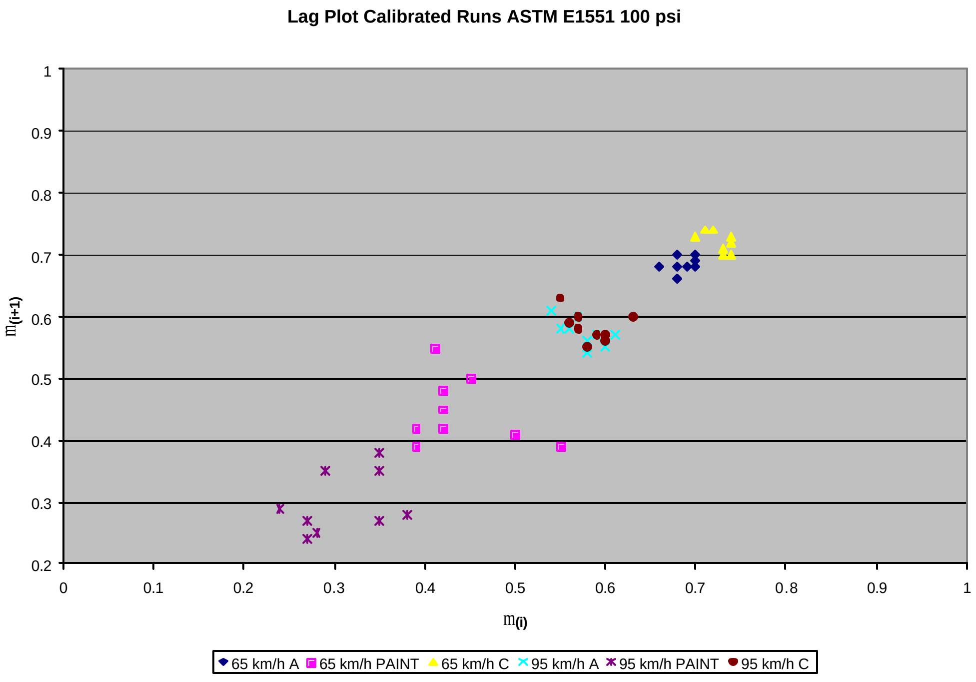


Figure 16. Lag plot for ASFT-810 after uniform calibration

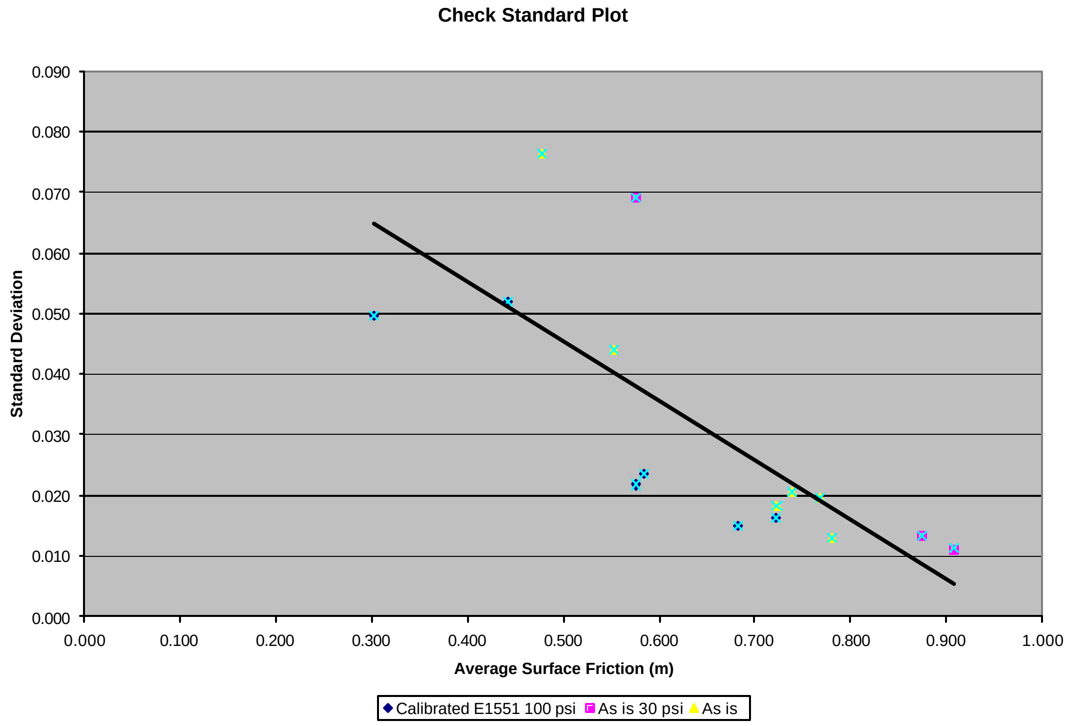


Figure 17. Check standard plot for ASFT-810

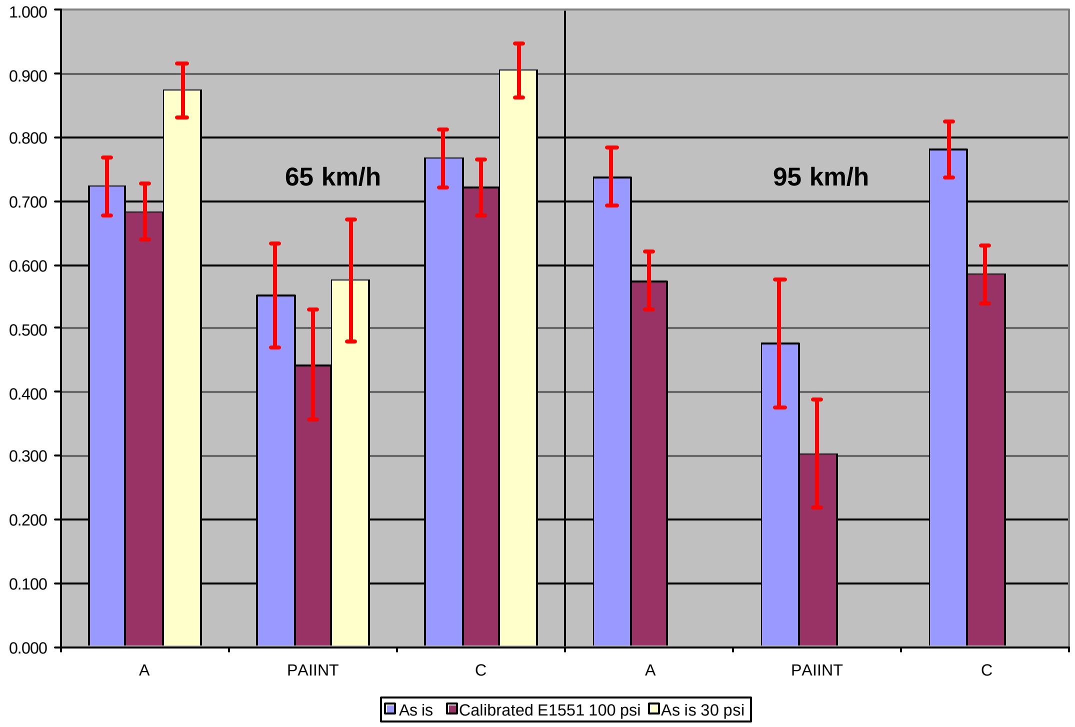


Figure 18. Repeatability plot for ASFT-810

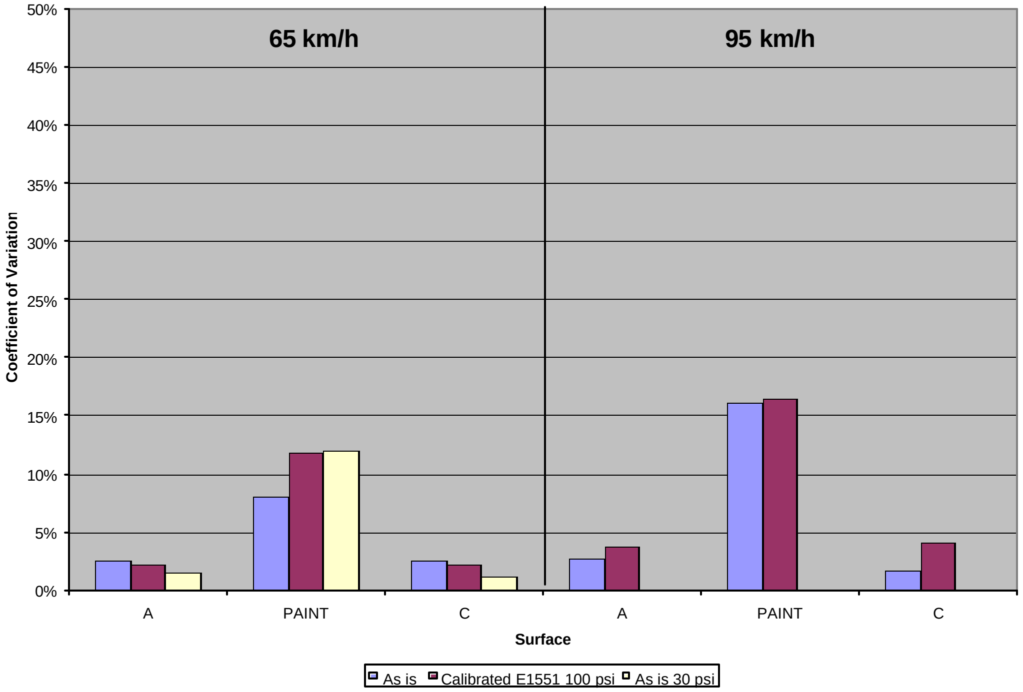


Figure 19. Coefficient of variation plot for ASFT-810

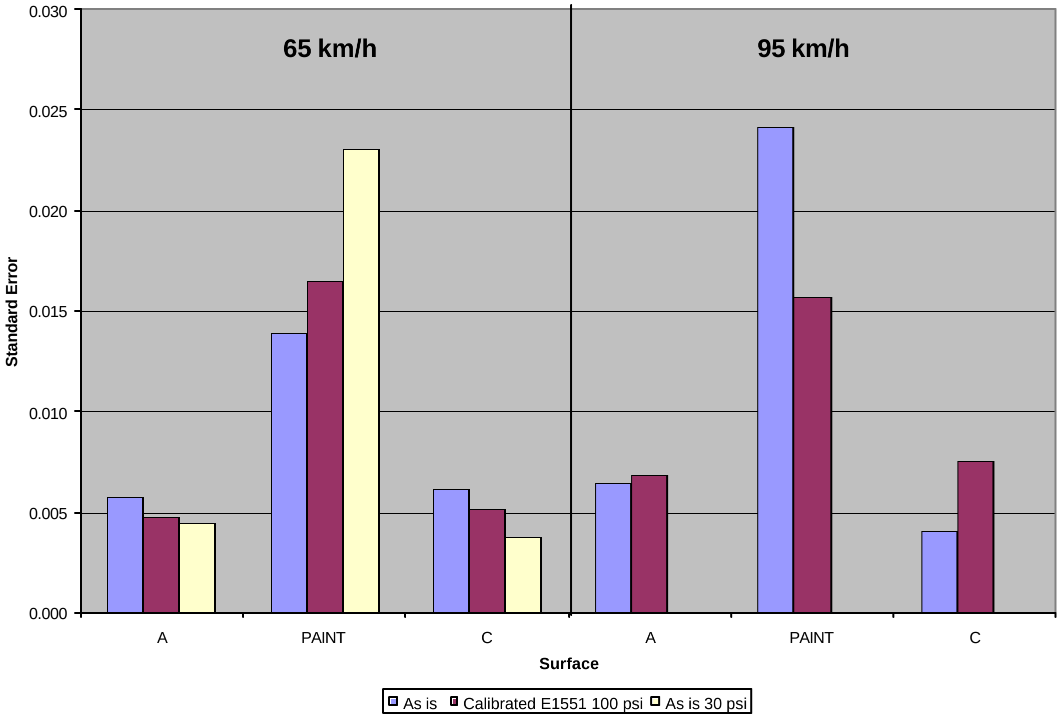


Figure 20. Standard error plot for ASFT-810

7.2.3 BV11-VIE

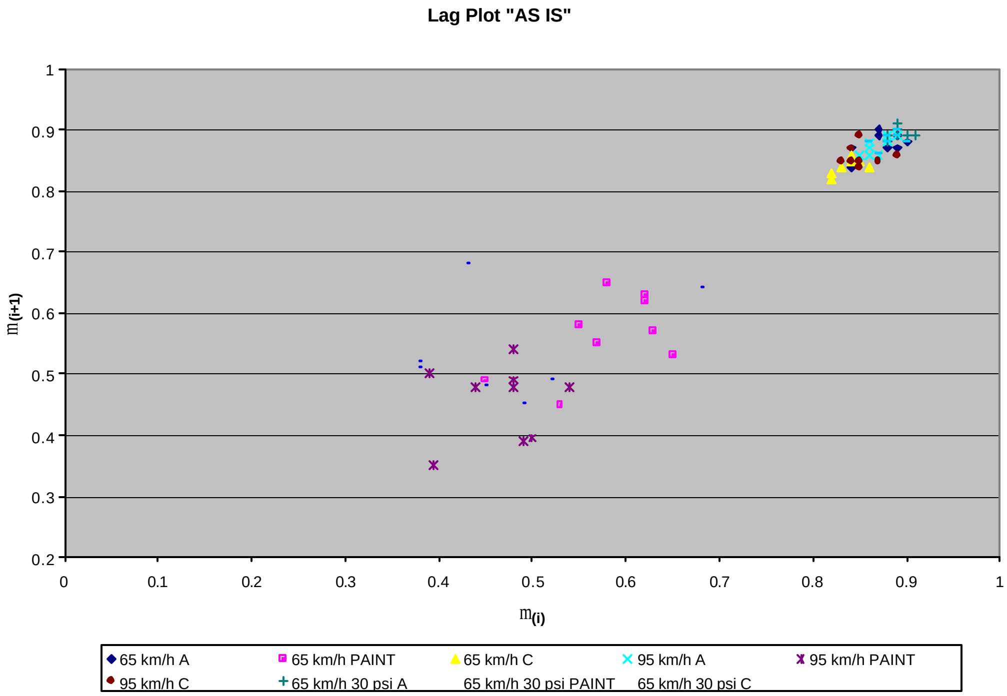


Figure 21. Lag plot for BV11-VIE before uniform calibration

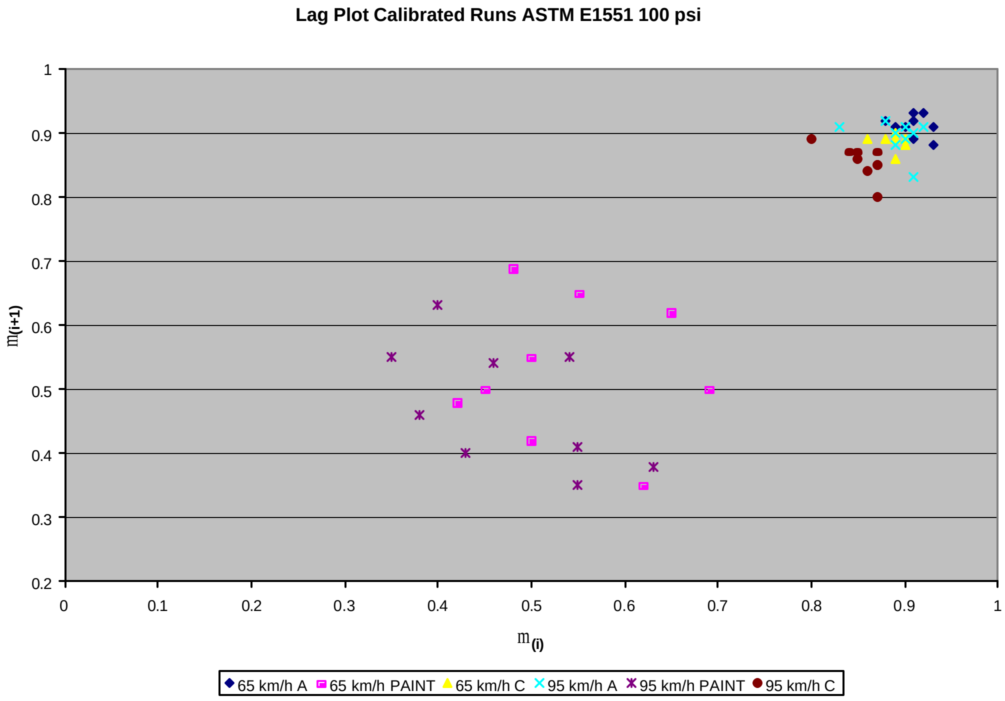


Figure 22. Lag plot for BV11-VIE after uniform calibration

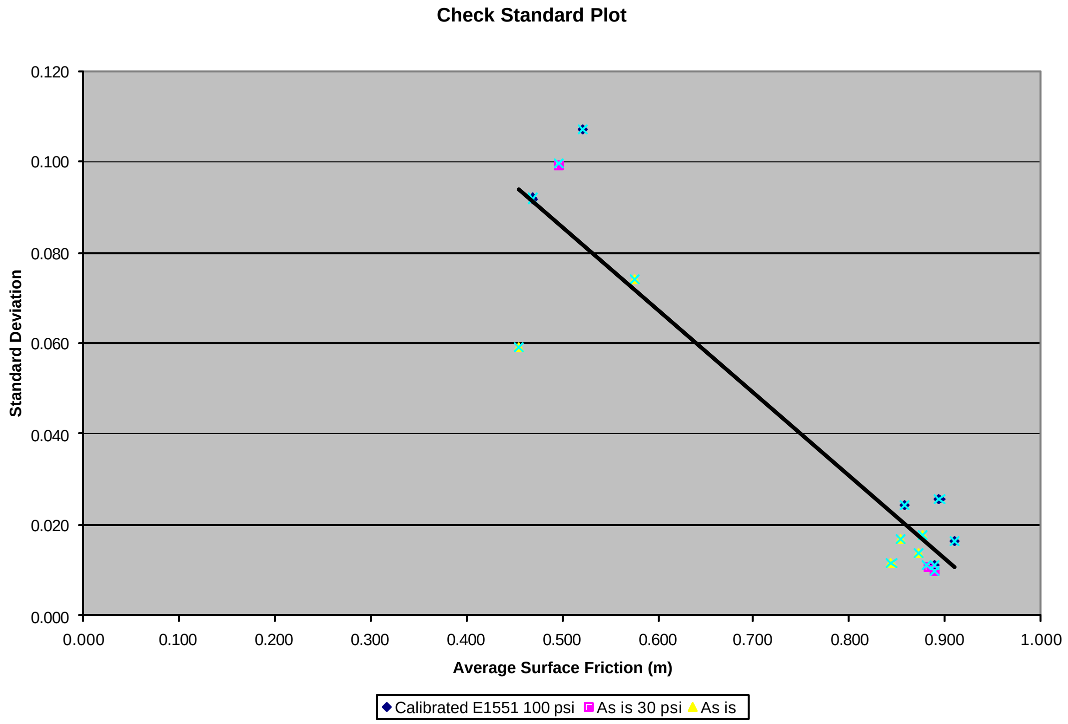


Figure 23. Check standard plot for BV11-VIE

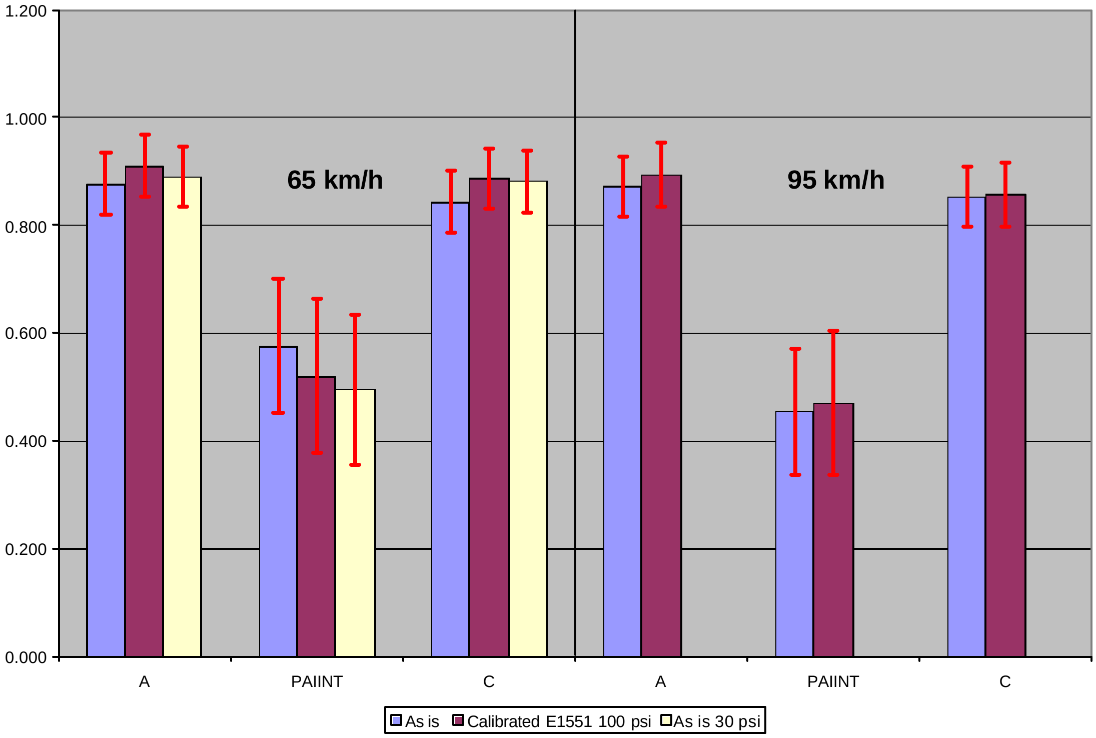


Figure 24. Repeatability plot for BV11-VIE

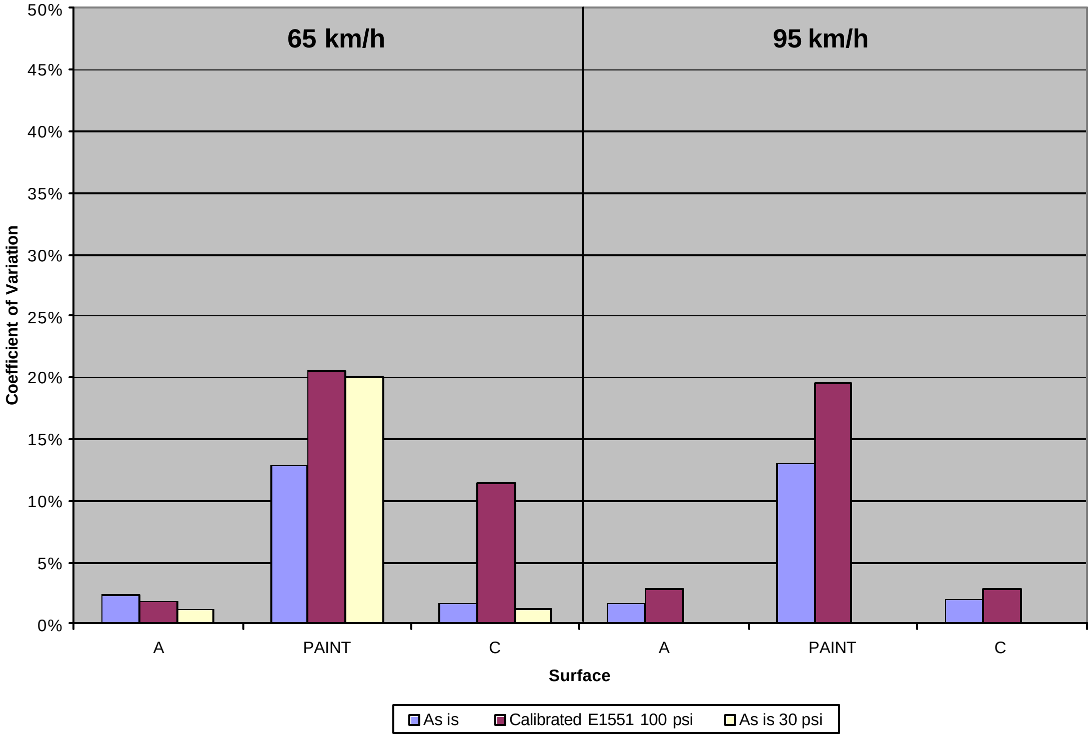


Figure 25. Coefficient of variation plot for BV11-VIE

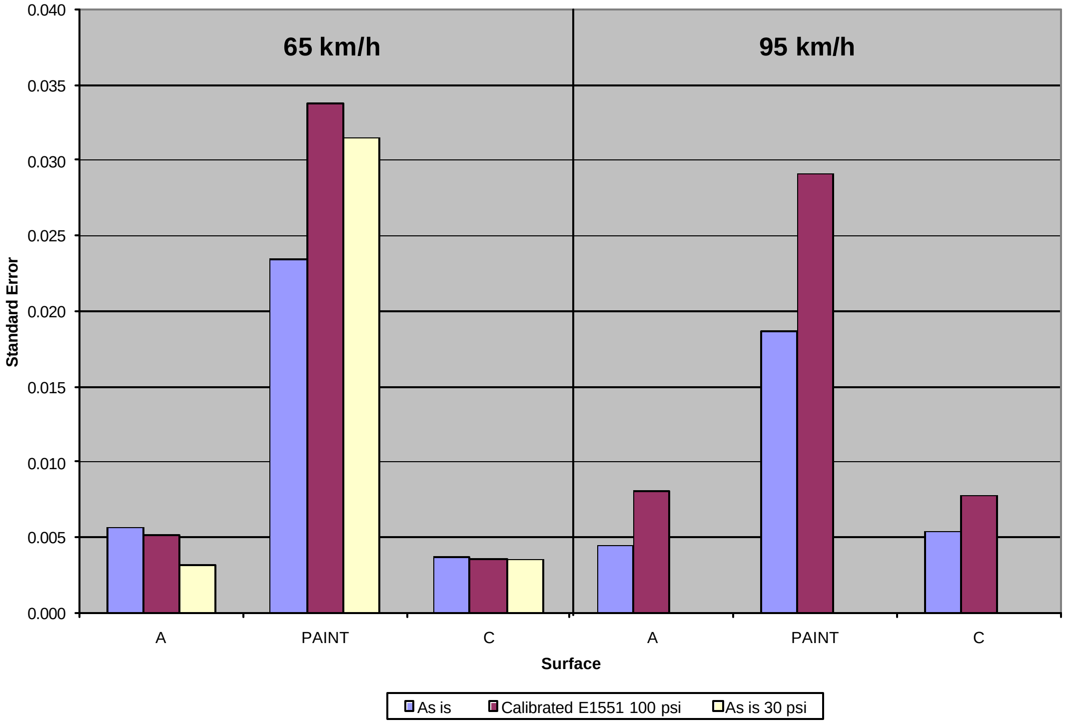


Figure 26. Standard error plot for BV11-VIE

7.2.4 SAR-813

The SAR-813 Saab friction measurement device from Düsseldorf had to be removed from the experiment after the second day of testing. The measured data by the device did not provide a sufficient amount of data for the uncertainty analysis to be performed. Therefore the device was dropped from the data analysis.

7.2.5 SAR-602

The SAR-602 Saab friction measurement device from Munich encountered several technical problems and malfunctioning throughout the testing and performed an inadequate number of tests to produce the uncertainty statistics. The actual measured data were very questionable and therefore this device was dropped from the data analysis.

7.2.6 SAR-527

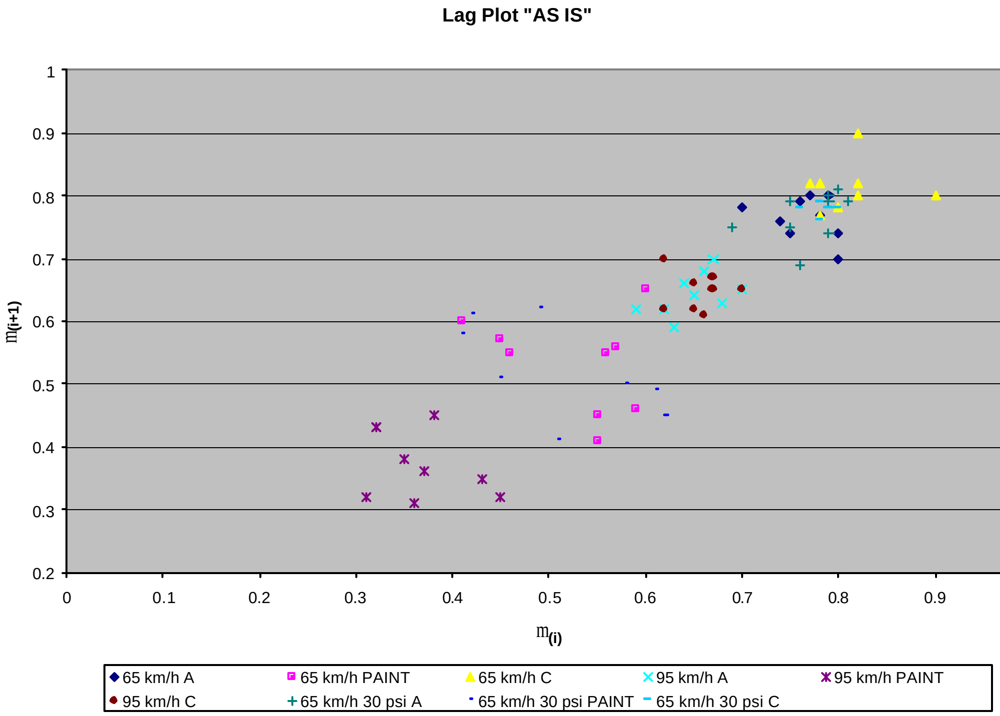


Figure 27. Lag plot for SAR-527 before uniform calibration

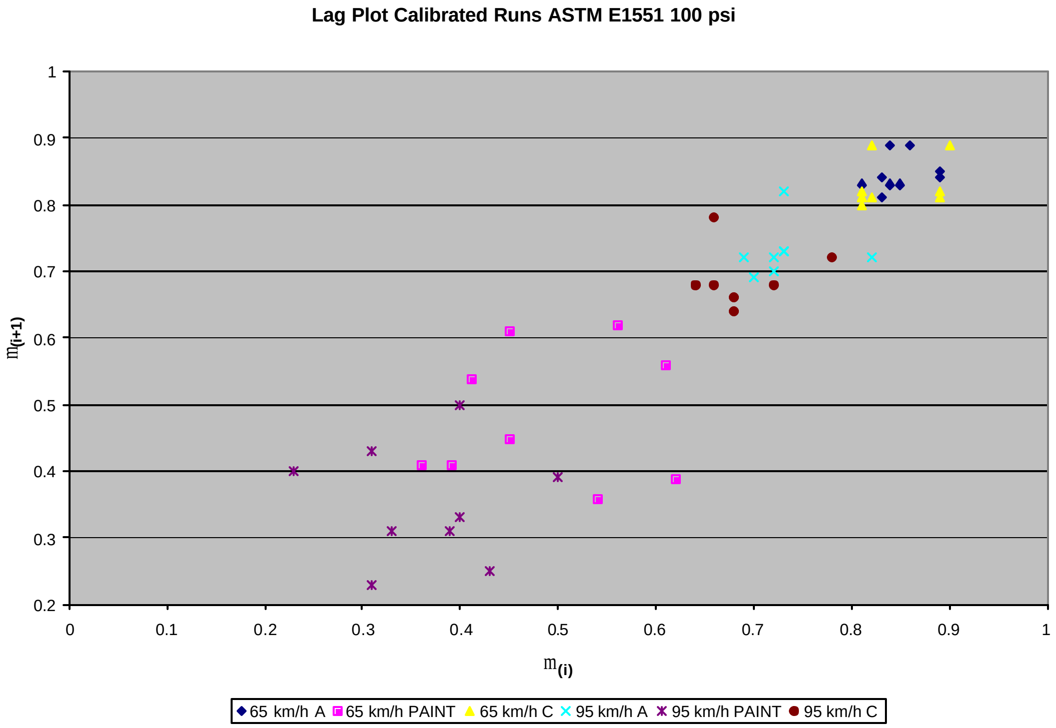


Figure 28. Lag plot for SAR-527 after uniform calibration

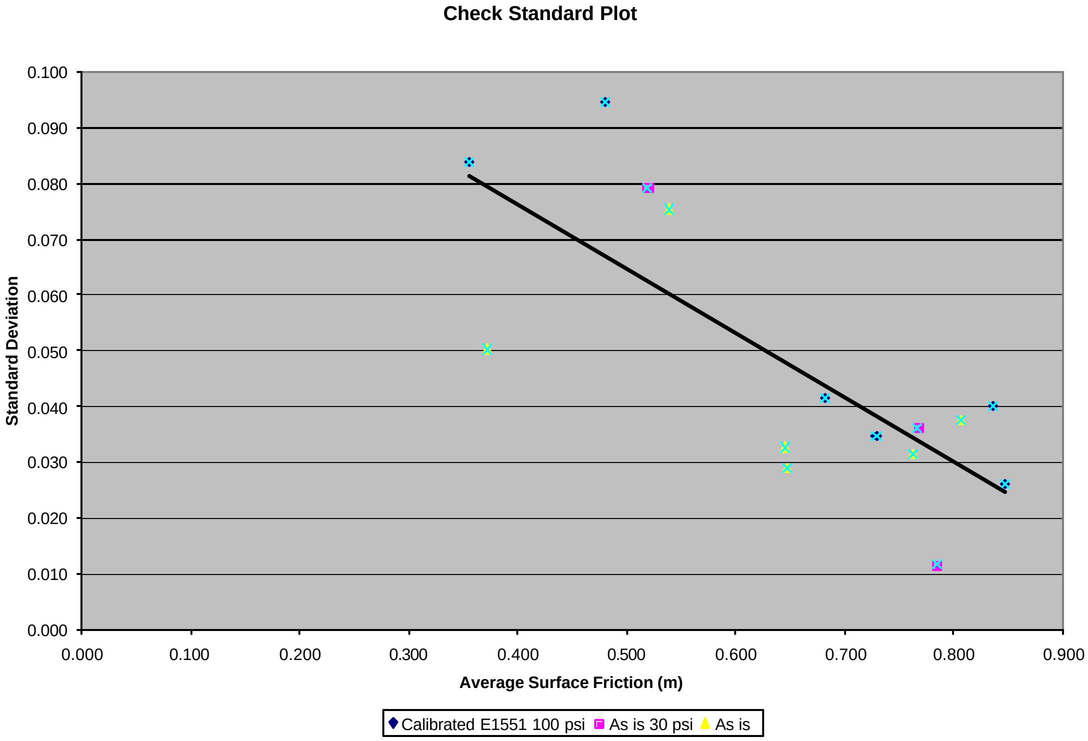


Figure 29. Check standard plot for SAR-527

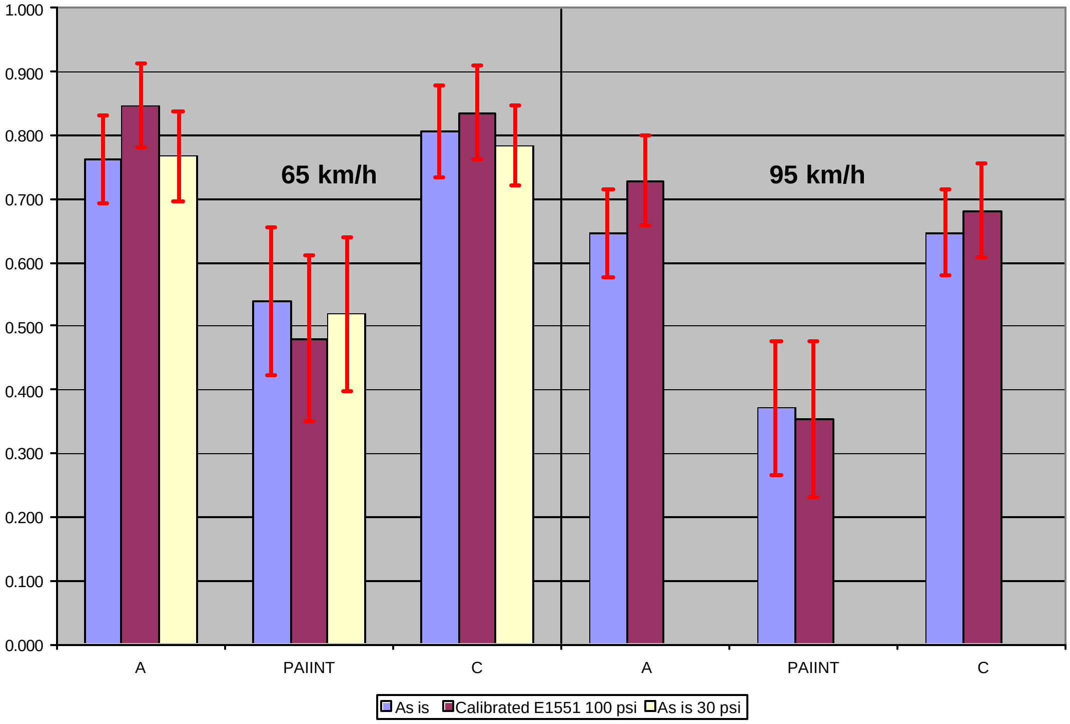


Figure 30. Repeatability plot for SAR-527

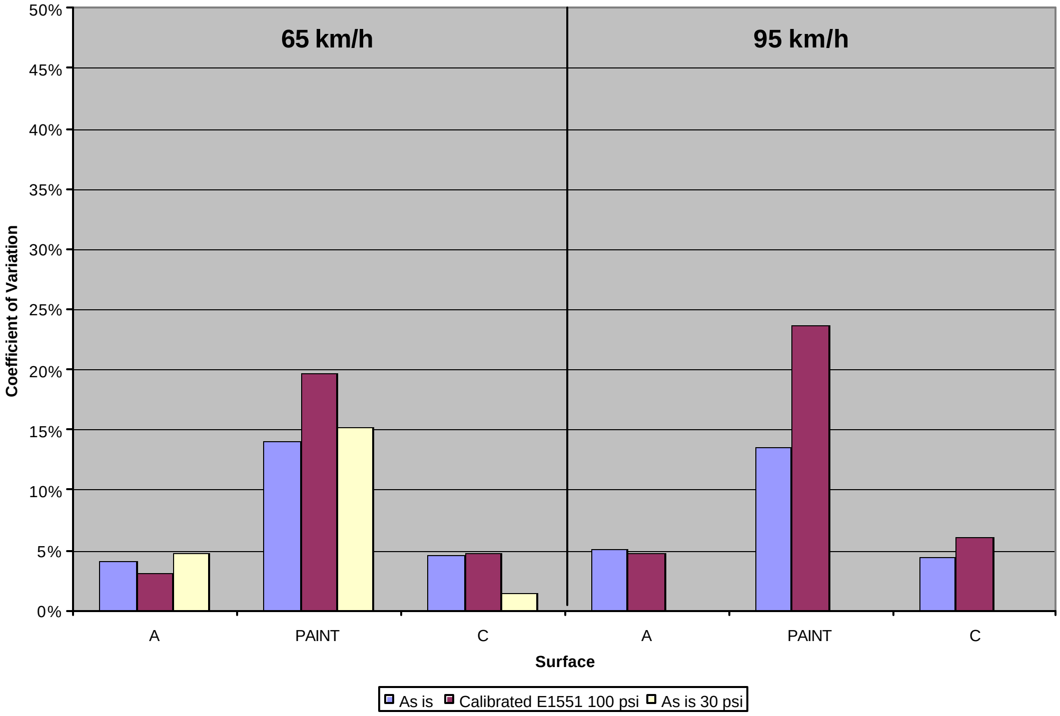


Figure 31. Coefficient of variation plot for SAR-527

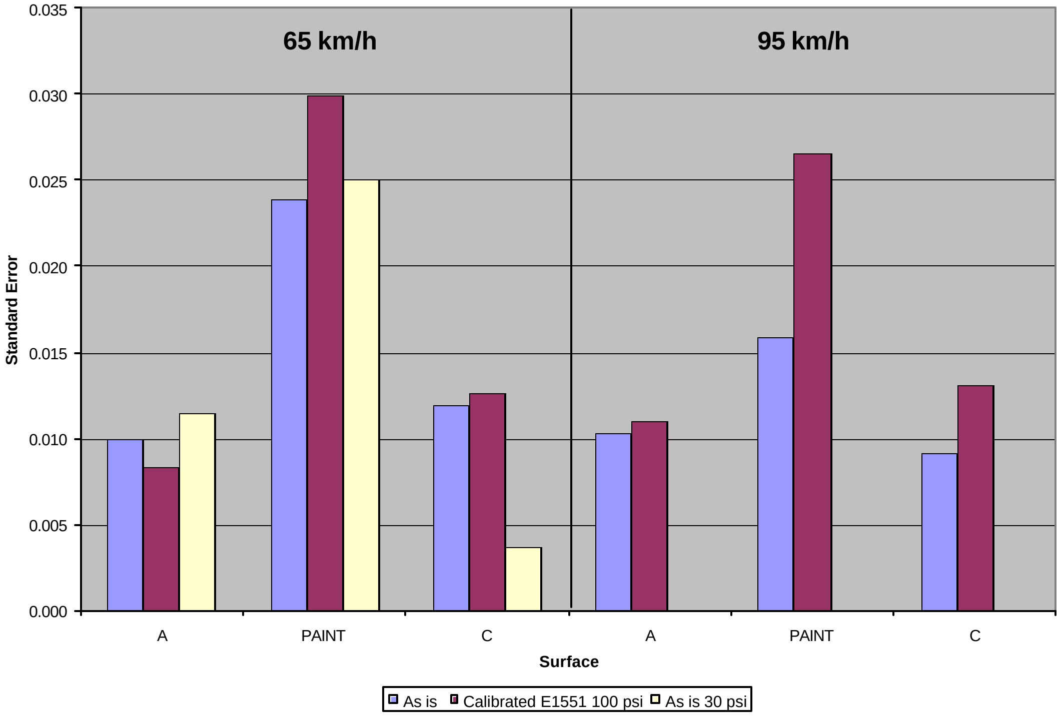


Figure 32. Standard error plot for SAR-527

7.2.7 SFT-511

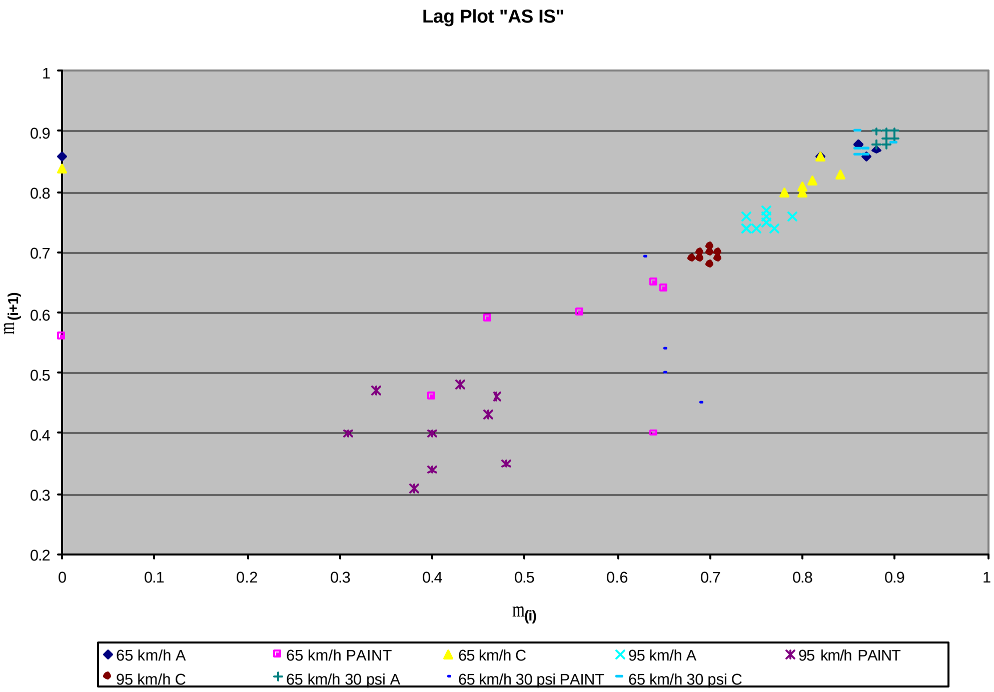


Figure 33. Lag plot for SFT-511 before uniform calibration

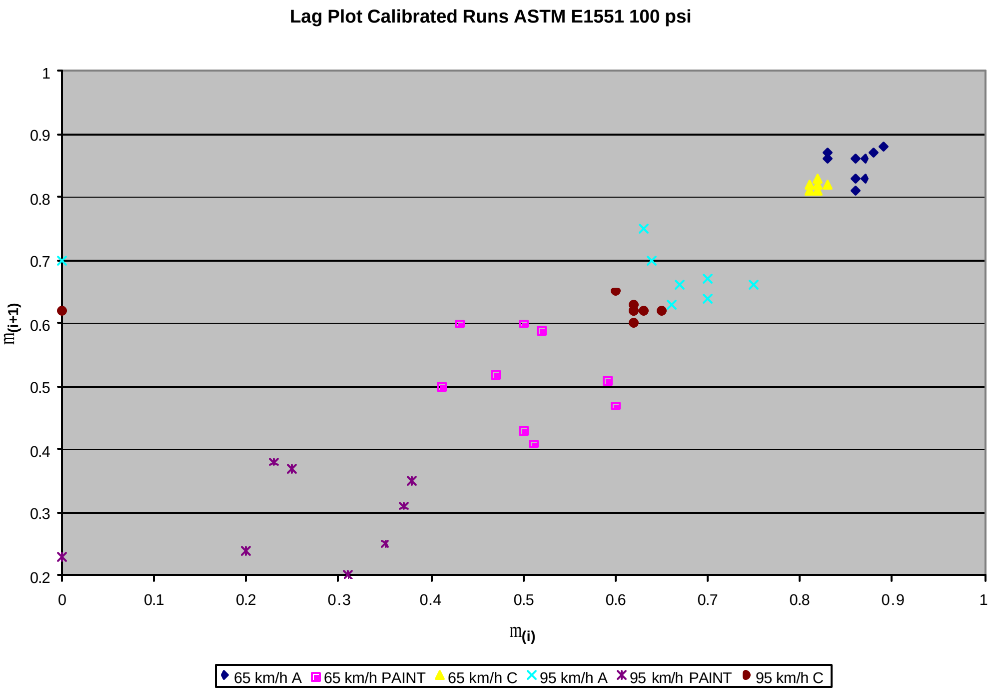


Figure 34. Lag plot for SFT-511 after uniform calibration

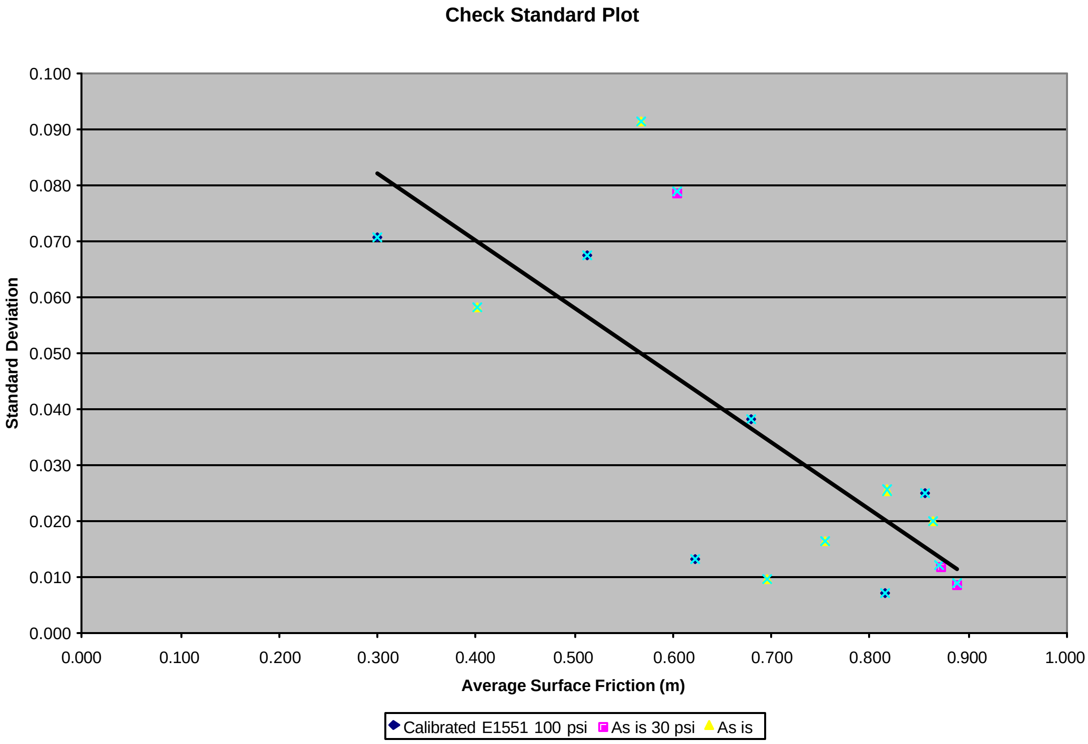


Figure 35. Check standard plot for SFT-511

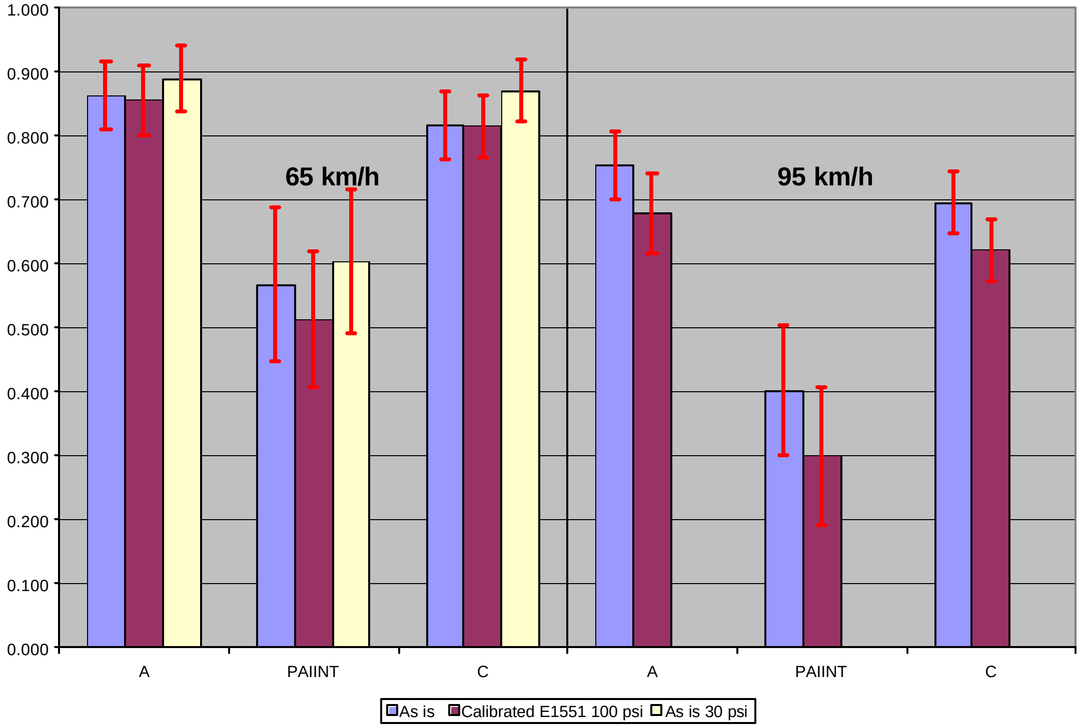


Figure 36. Repeatability plot for SFT-511

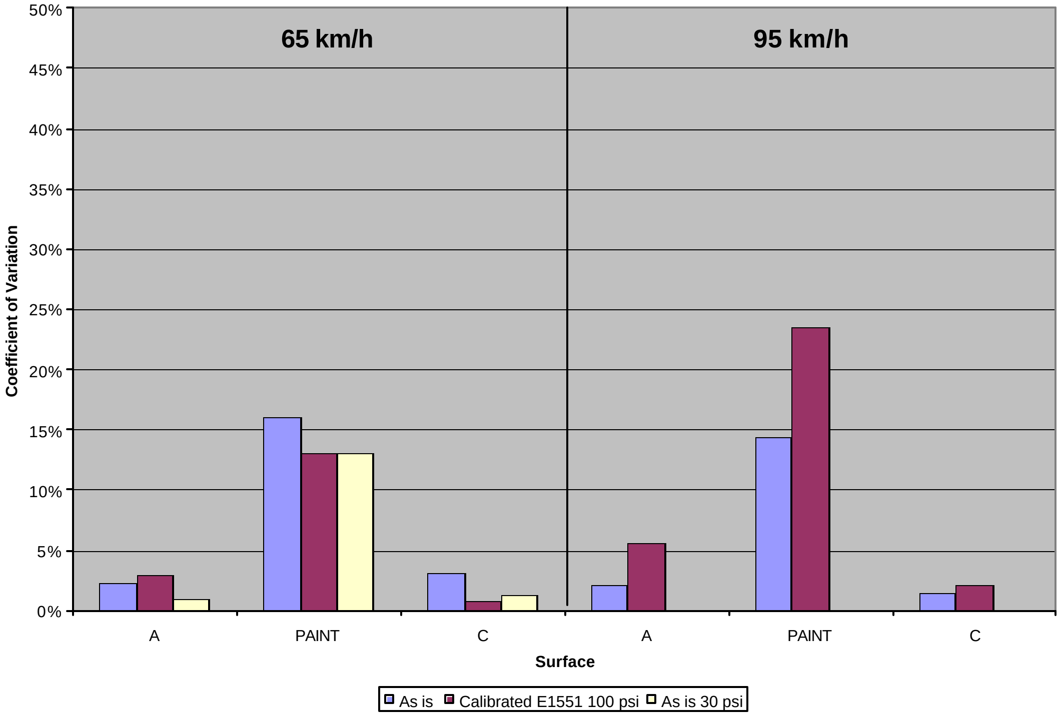


Figure 37. Coefficient of variation plot for SFT-511

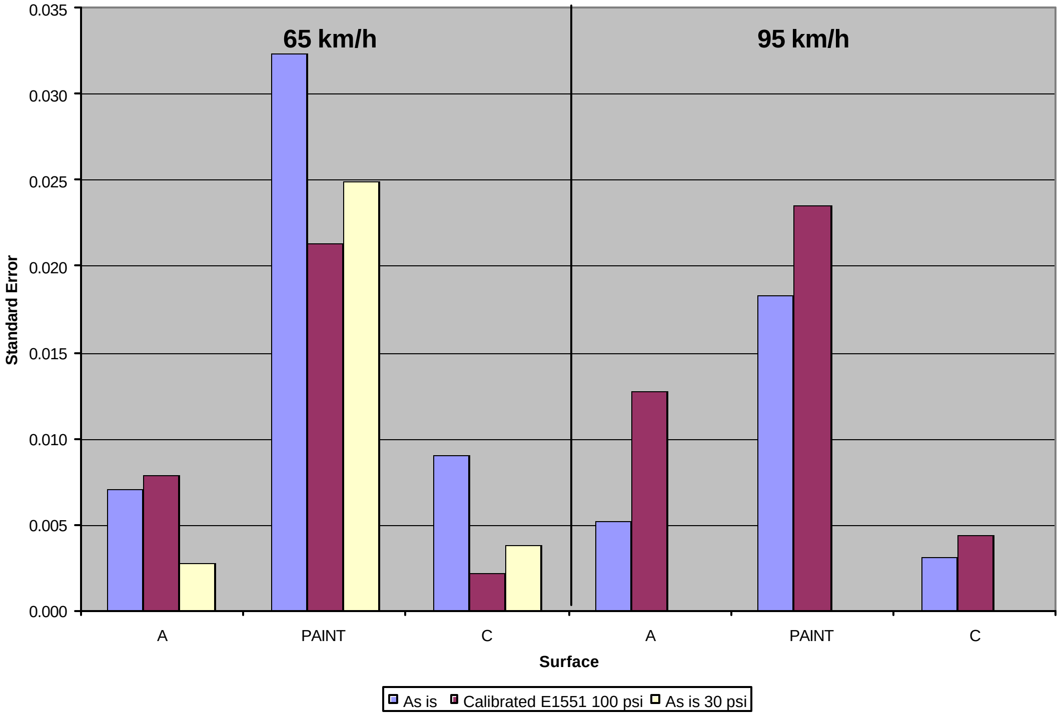


Figure 38. Standard error plot for SFT-511

7.2.8 SFT-212

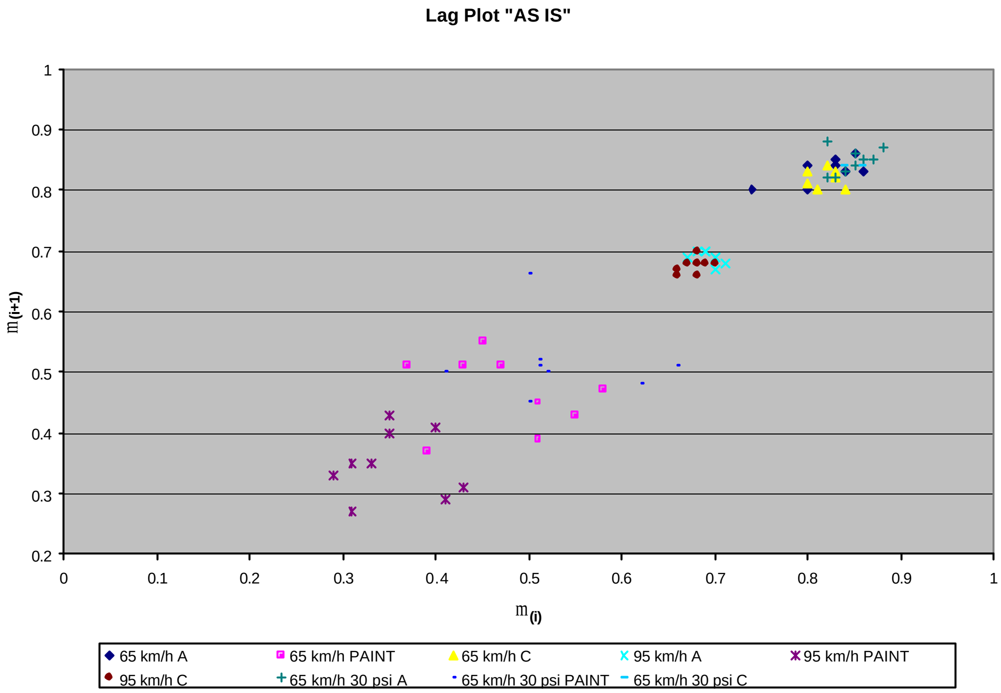


Figure 39. Lag plot for SFT-212 before uniform calibration

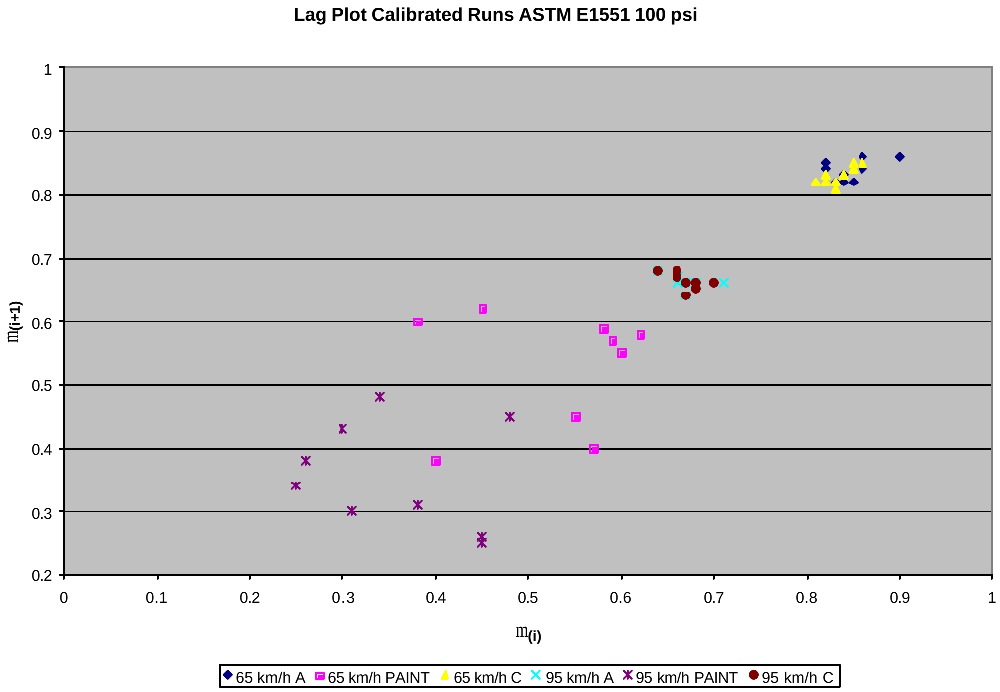


Figure 40. Lag plot for SFT-212 after uniform calibration

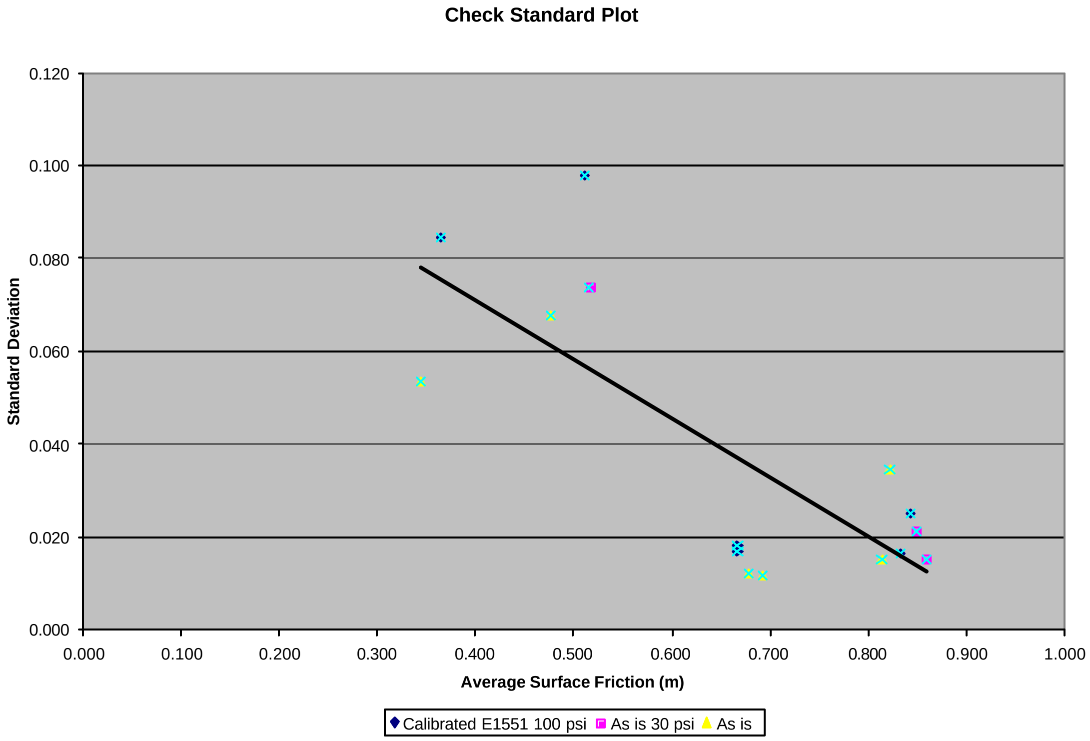


Figure 41. Check standard plot for SFT-212

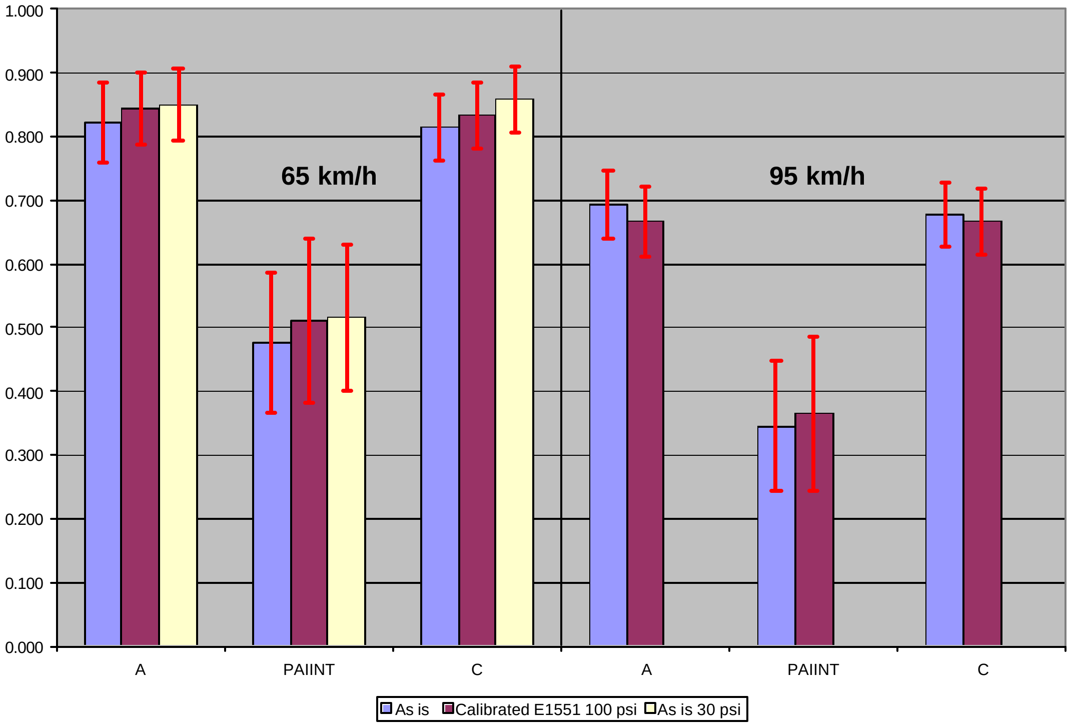


Figure 42. Repeatability plot for SFT-212

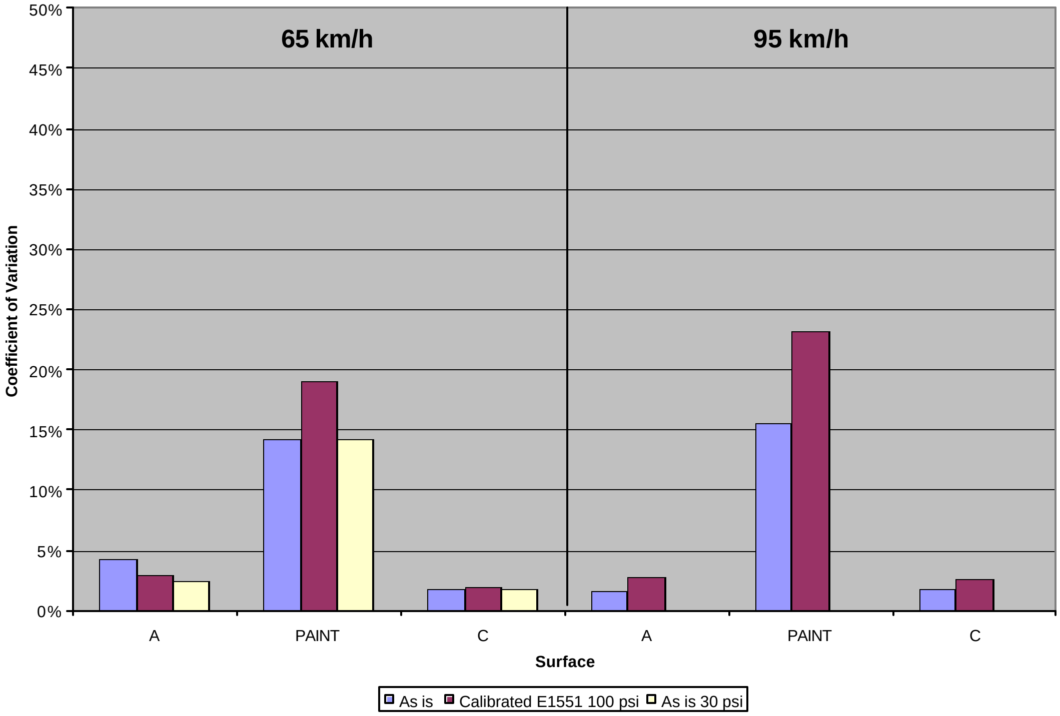


Figure 43. Coefficient of variation plot for SFT-212

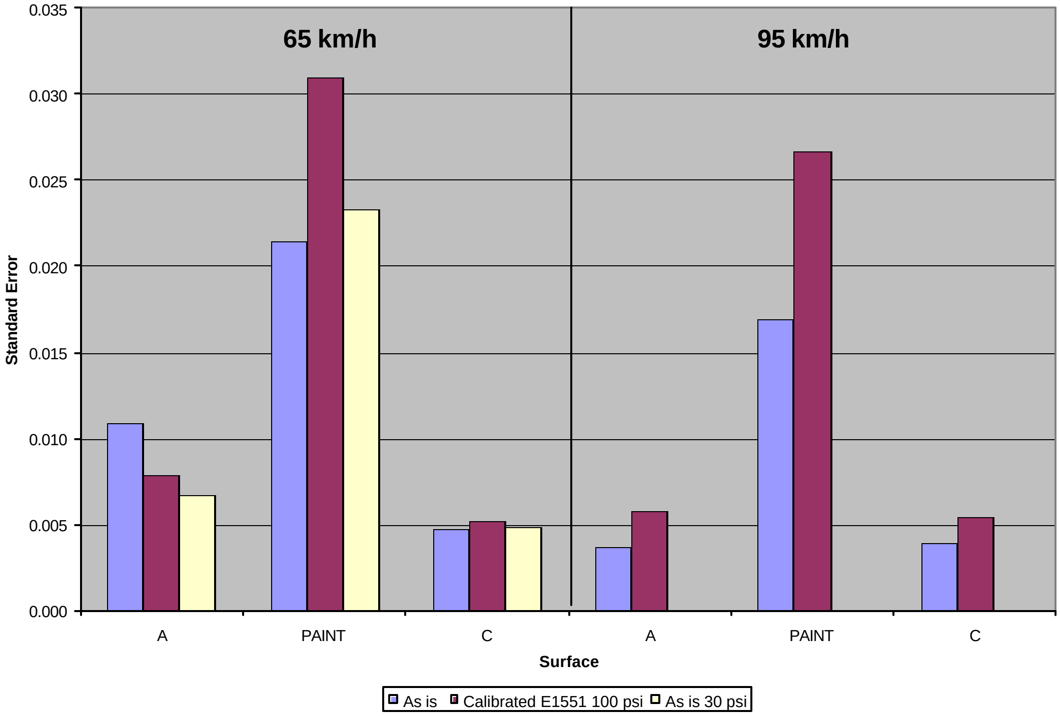


Figure 44. Standard error plot for SFT-212

7.2.9 SAR-805

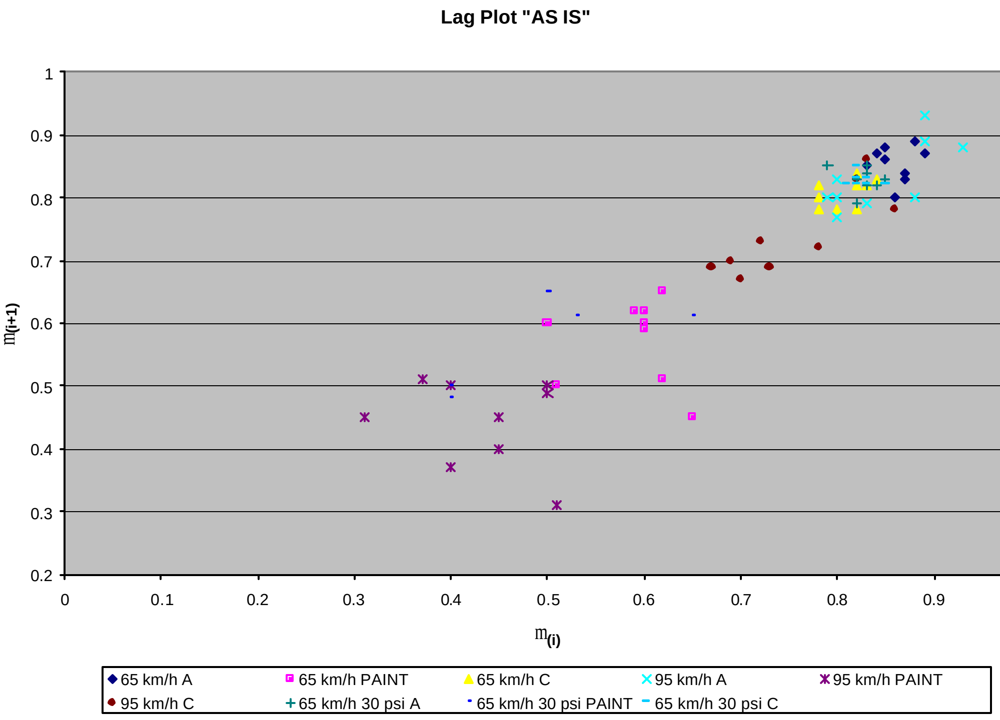


Figure 45. Lag plot for SAR-805 before uniform calibration

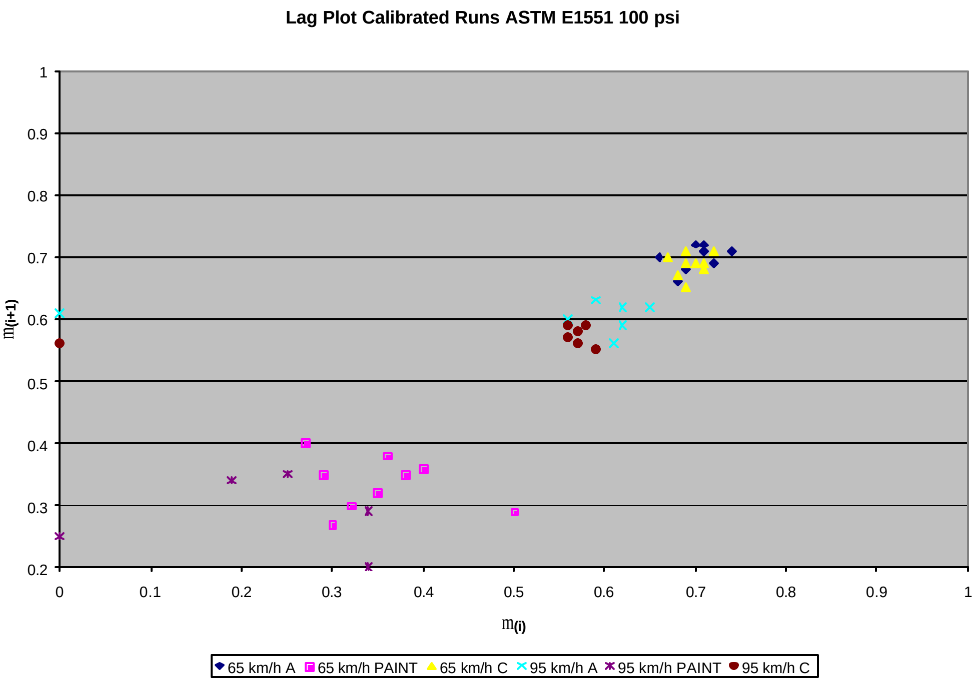


Figure 46. Lag plot for SAR-805 after uniform calibration

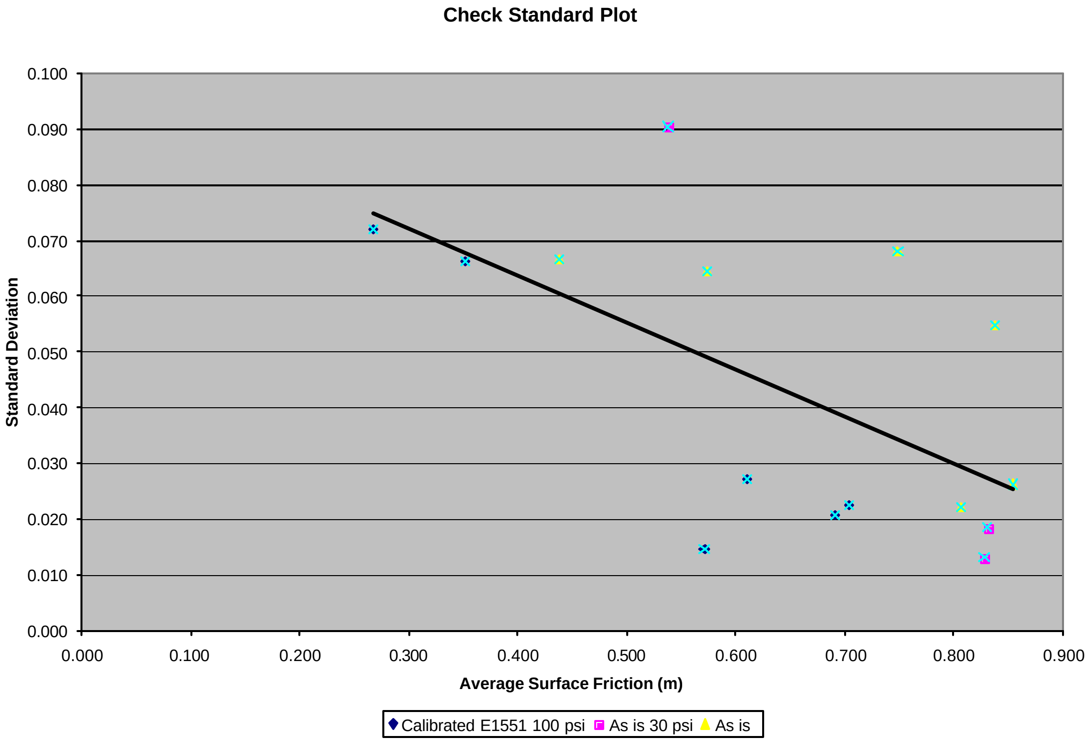


Figure 47. Check standard plot for SAR-805

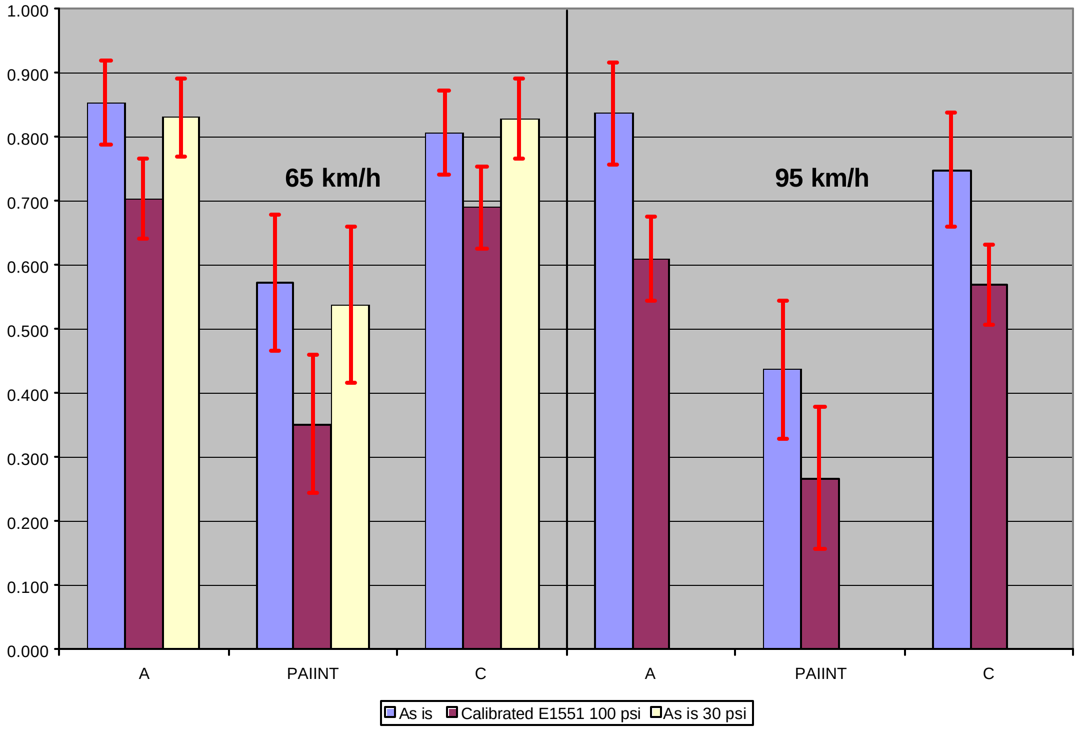


Figure 48. Repeatability plot for SAR-805

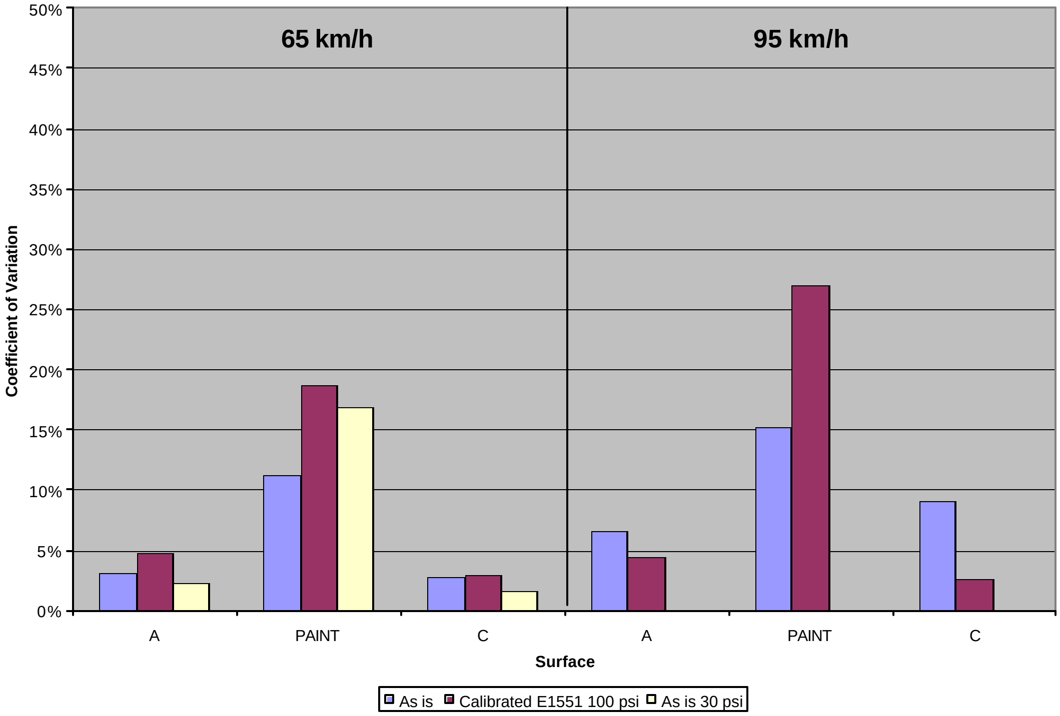


Figure 49. Coefficient of variation plot for SAR-805

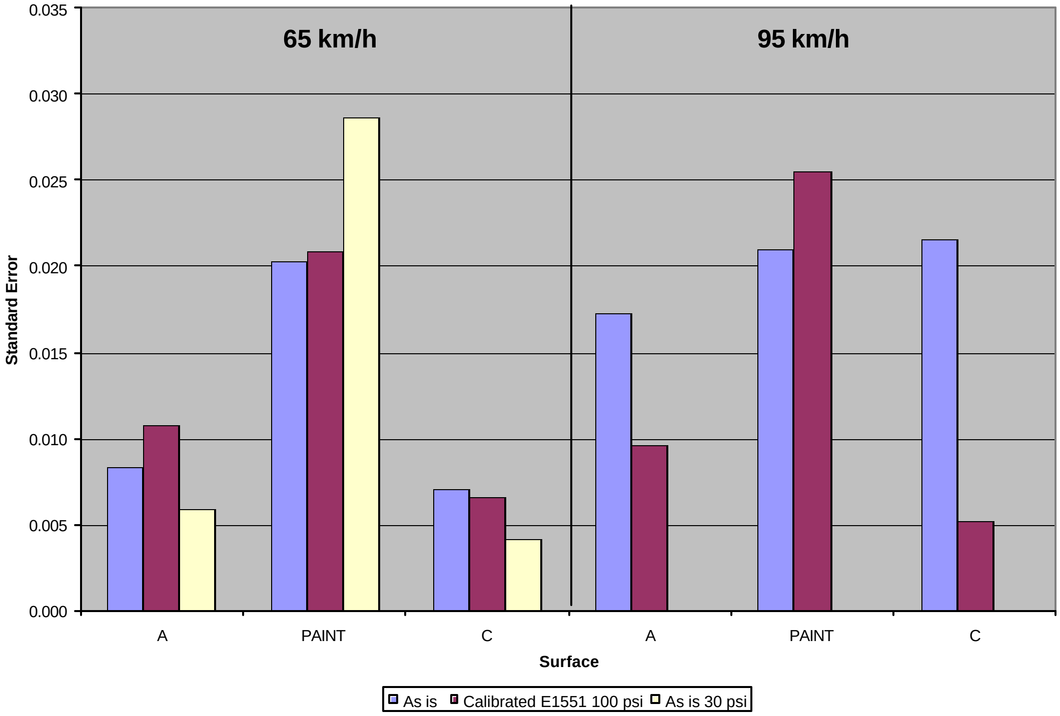


Figure 50. Standard error plot for SAR-805

7.2.10 SAR-814

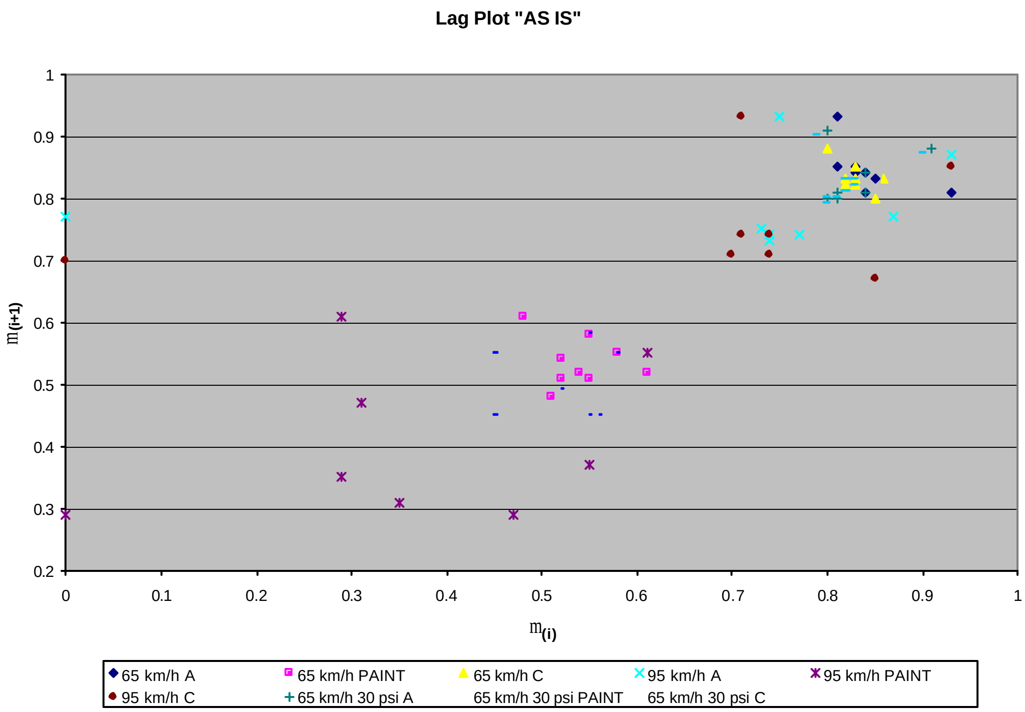


Figure 51. Lag plot for SAR-814 before uniform calibration

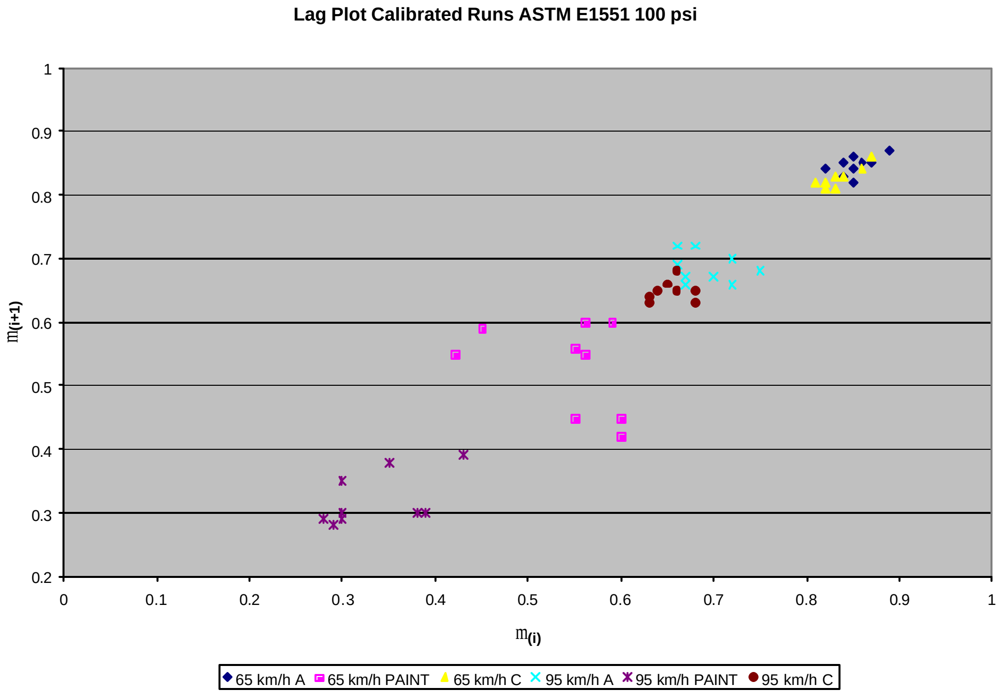


Figure 52. Lag plot for SAR-814 after uniform calibration

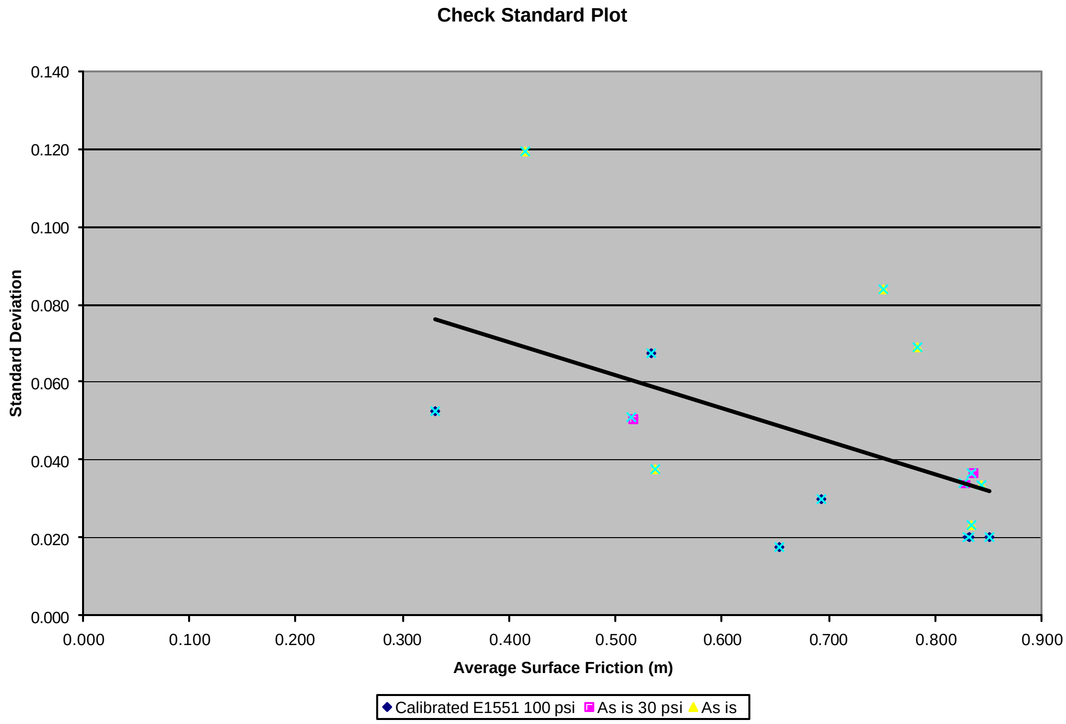


Figure 53. Check standard plot for SAR-814

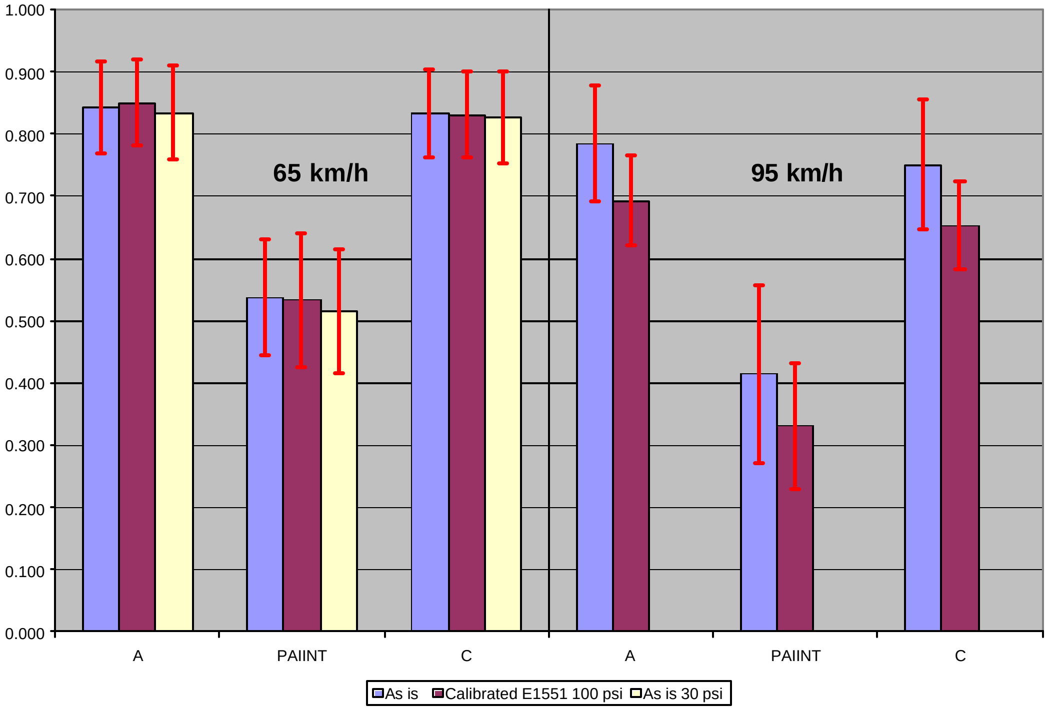


Figure 54. Repeatability plot for SAR-814

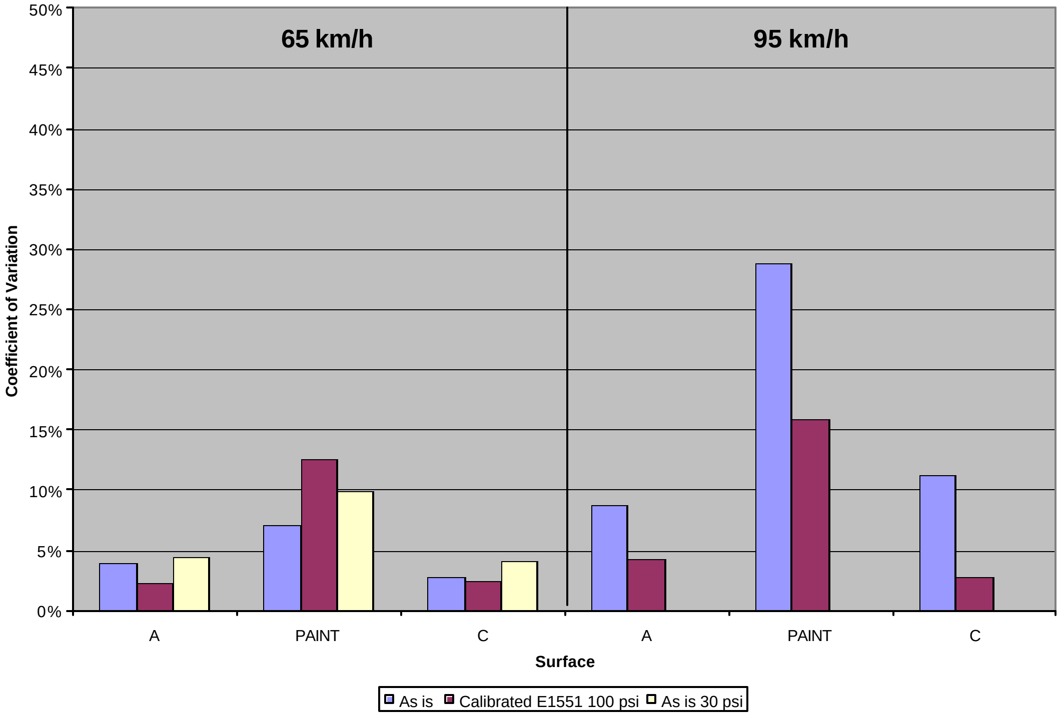


Figure 55. Coefficient of variation plot for SAR-814

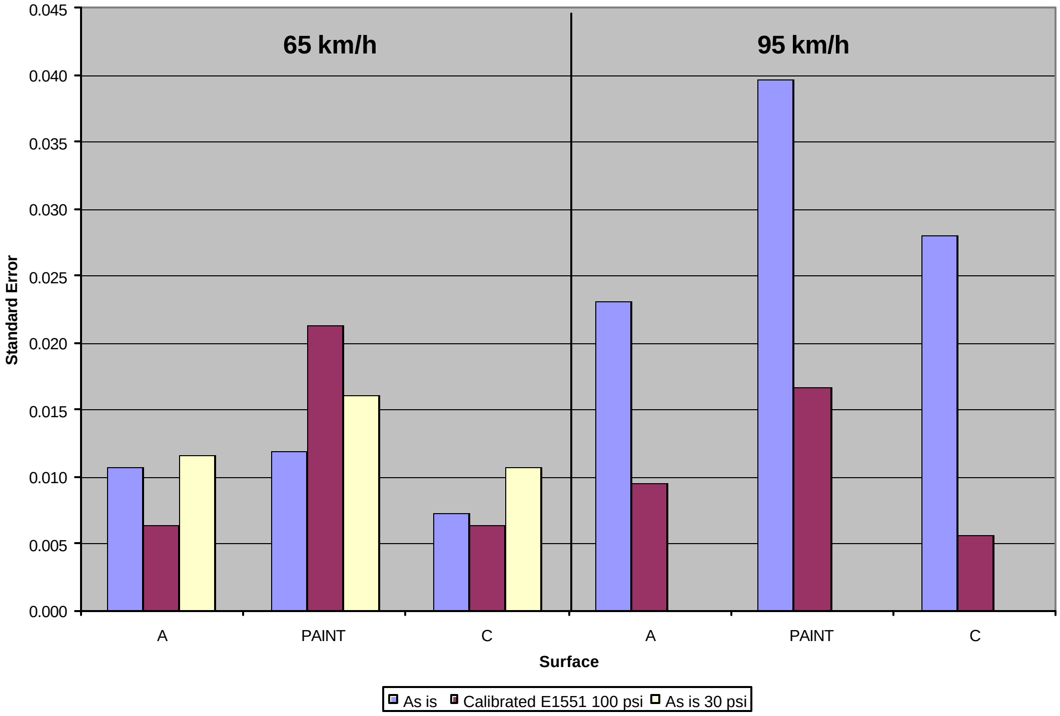


Figure 56. Standard error plot for SAR-814

7.3 Reproducibility statistics

For the reproducibility analysis, the repeated measurement runs of the different devices were processed according to the ISO standard to provide the three levels of uncertainty standard deviations. The devices' repeated measurements for the different test projects were averaged and the device repeatability Level-2 standard deviations calculated. Level-1 reproducibility standard deviations were also calculated for the different measurement waves amongst the different devices. The Level-1 and Level-2 deviations were then pooled statistically to provide the Level-3 repeatability standard deviations for the family of Saab friction measurement devices.

The following plots are presented for the reproducibility statistics of the Saab friction measurement device family.

1. ***Reproducibility Plot***. The reproducibility plot is the plot of the pooled Level-3 reproducibility standard deviations of the family of measurement devices for the different surfaces with base as the average measurement value amongst the participating measurement devices. This graph is a standard bar chart containing the average of the pooled measurement runs for the different sessions on the different surfaces. With regard to the different speeds, the reproducibility standard deviation is plotted on the corresponding bars as a standard error bar.
2. ***Coefficient of Variation Plot***. The coefficient of variation plot depicts the calculated coefficient of variation statistics for a family of measurement devices in one graph for the different surfaces and measurement target speeds grouped for the different measurement sessions.
3. ***Standard Error Plot***. The standard error plot depicts the calculated standard error statistics for the family of measurement devices in one graph for the different surfaces and measurement target speeds grouped for the different measurement sessions.

Figure 57 shows the calculated total pooled Level-3 reproducibility standard deviations for each measurement session. As can be easily observed from the figure, the measurement devices produced better reproducibility for higher nominal friction values and the reproducibility worsened for lower friction ranges.

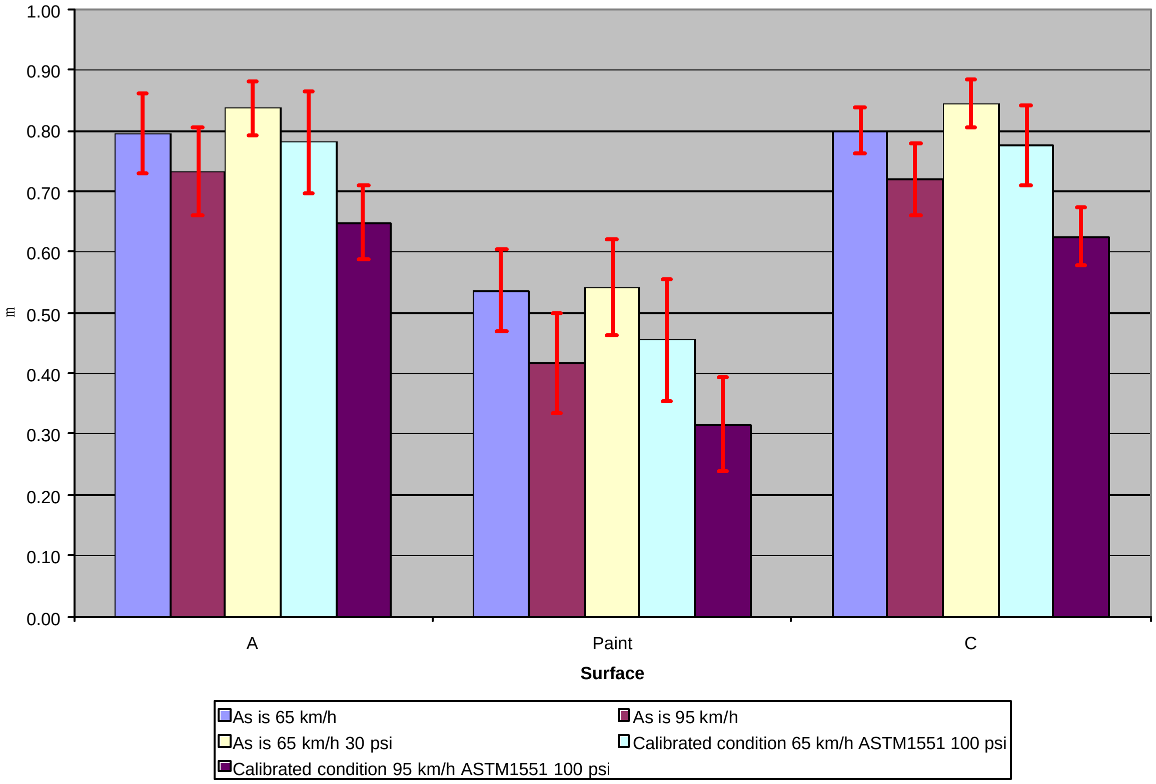


Figure 57. Reproducibility plot for the Saab equipment family

Please note that the indicated friction ranges in Figure 57 are NOT confidence intervals but rather the true uncertainty measures for the family of Saab friction measurement devices. The figure indicates that the use of the ASTM 1551 measurement tire increases the resolution of the devices; the differences between the nominal friction values between the different sections are increased. It also shows that the total uncertainty in the Saab measurement equipment family can be reduced by the use of the ASTM 1551 measurement tire.

The data in Figure 57 also indicates that the measurement device does not show significant repeatability variation with regard to the measurement speed.

It can also be seen that the reduction of the tire pressure also indicates a relevant reduction of overall uncertainty in the measurement device family.

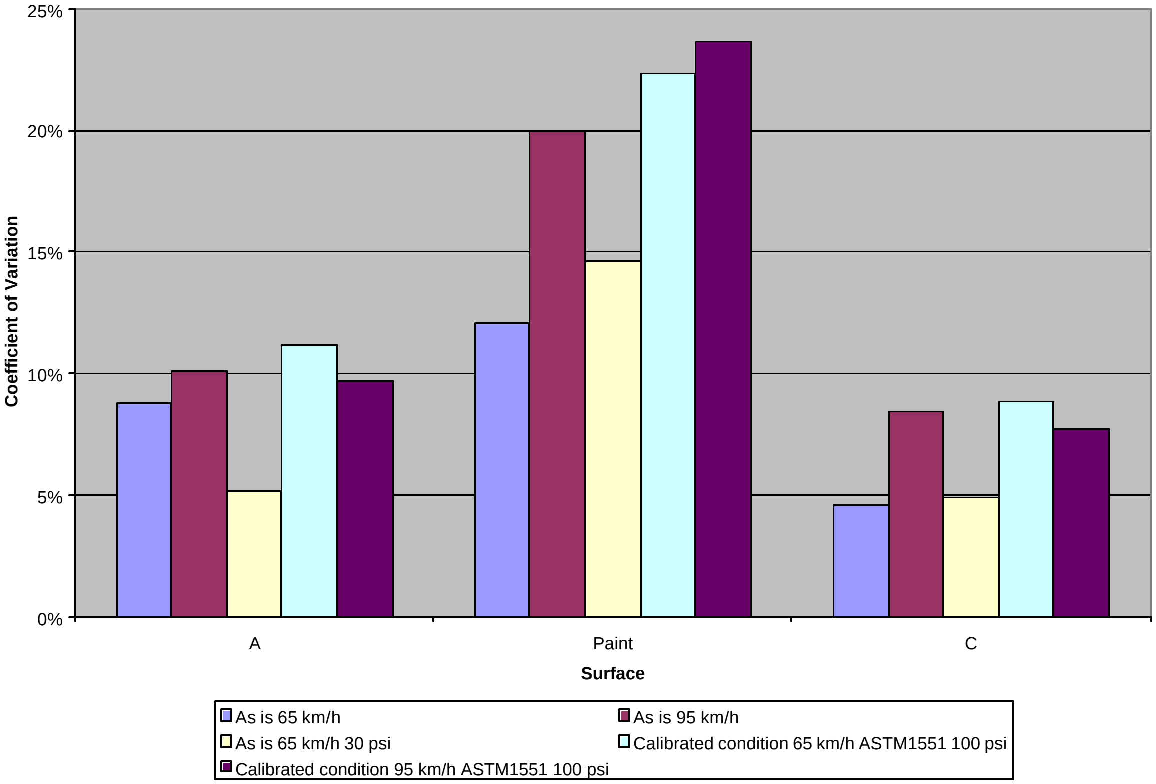


Figure 58. Coefficient of variation plot for the Saab equipment family

The coefficient of variation data shown in Figure 58 indicates the general tendencies shown in Figure 57. However, the statistic cannot disregard the differences of the nominal measurement values introduced by some unknown physical phenomena during the standard calibration procedure. The devices were calibrated by the same equipment and by the same calibration crew during the testing. The data indicates a significant and unknown physical process that was encountered during this process. Figure 60 shows the data measured by the various devices immediately after the standard calibration procedure. The data indicates that the measurement devices were calibrated to some different levels that divided the group of measurement devices into two distinct clusters.

Using the standard error and the coefficient of variation statistics, this clustering of the data is pronounced in the analysis. In Figure 58 this is indicated by the higher or equal values of the coefficients of variation parameters for the measurements done after the calibration session. This also can be observed in Figure 59, although the speed-related uncertainty is dominating some of the data.

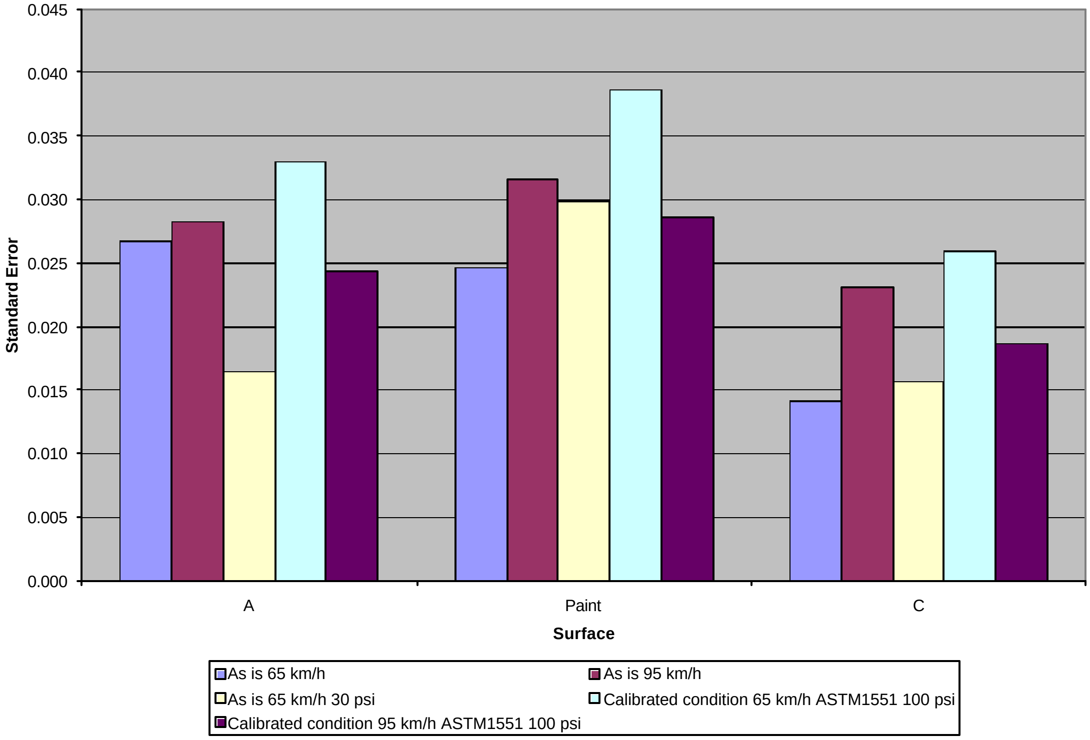


Figure 59. Standard error plot for the Saab equipment family

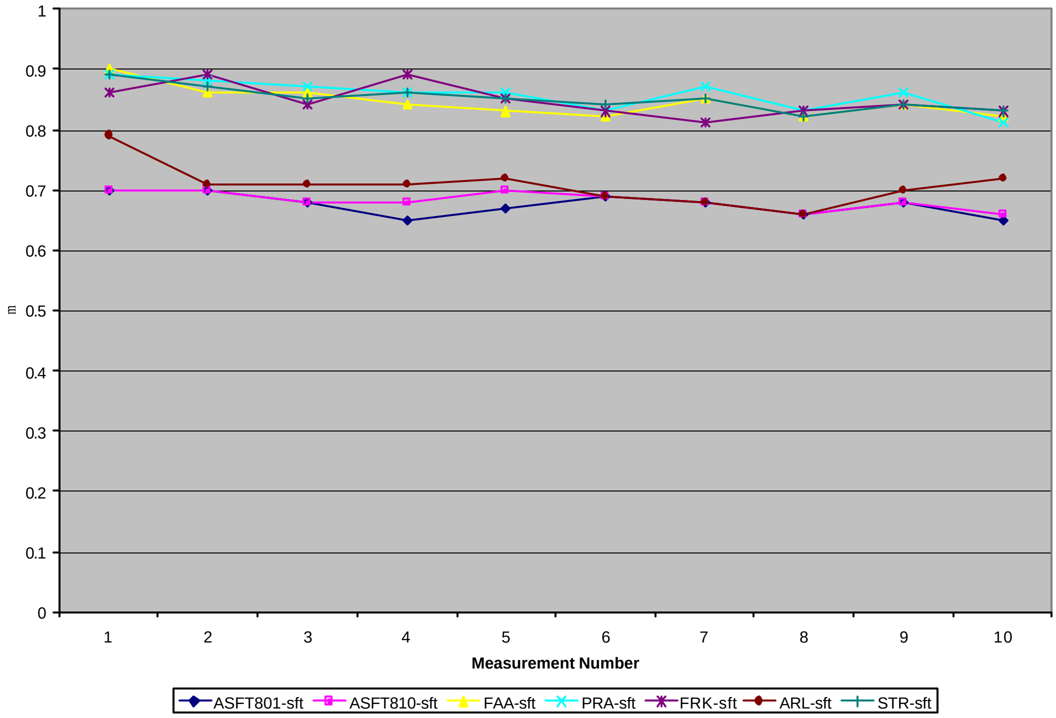


Figure 60. Measurement data immediately after standard calibration

8 RESULTS

This section gives a concise short picture of the results from the analysis given in the previous section. The analyzed data was compiled and the repeatability statistics were tabulated. Table 9 contains the calculated repeatability statistics for each device and for each measurement session. Table 9 shows the Level-1, Level-2 and Level-3 repeatability standard deviations, where the equations (2) and (3) where used to calculate the Level-1 repeatability standard deviation for each repeated measurements. Equations (11) and (13) were used to calculate the Level-2 repeatability standard deviation for each test surface: test surface A, test surface PAINT, and test surface C.

Equation (14) was used to calculate the Level-3 repeatability standard deviation.

8.1 Repeatability statistics

Table 9. Calculated repeatability statistics

				ASFT-801	ASFT-810	SFT-527	SFT-511	SFT-212	SFT-805	SFT-814	BV-11
LEVEL-1 STDEV	As is	65 km/h	A	0.023	0.018	0.032	0.020	0.035	0.026	0.015	0.018
			PAINT	0.061	0.044	0.075	0.091	0.068	0.064	0.038	0.074
			C	0.020	0.019	0.020	0.025	0.015	0.022	0.023	0.012
	As is	95 km/h	A	0.025	0.020	0.033	0.016	0.012	0.055	0.069	0.014
			PAINT	0.059	0.076	0.050	0.058	0.054	0.066	0.119	0.059
			C	0.009	0.013	0.029	0.010	0.012	0.068	0.084	0.017
	As is 30 psi	65 km/h	A	0.011	0.013	0.036	0.009	0.021	0.019	0.037	0.010
			PAINT	0.076	0.069	0.079	0.079	0.074	0.090	0.051	0.099
			C	0.007	0.011	0.012	0.007	0.015	0.013	0.034	0.011
	Calibrated E1551 100 psi	65 km/h	A	0.018	0.015	0.026	0.025	0.025	0.023	0.020	0.016
			PAINT	0.080	0.052	0.095	0.067	0.098	0.066	0.067	0.107
			C	0.020	0.016	0.040	0.007	0.016	0.021	0.020	0.011
	Calibrated E1551 100psi	95 km/h	A	0.015	0.022	0.015	0.038	0.018	0.027	0.030	0.025
			PAINT	0.080	0.050	0.084	0.071	0.084	0.072	0.053	0.092
			C	0.021	0.024	0.042	0.013	0.017	0.015	0.018	0.025
LEVEL-2 STDEV			A	0.085	0.108	0.074	0.088	0.088	0.106	0.065	0.015
			PAINT	0.105	0.108	0.085	0.125	0.082	0.127	0.091	0.048
			C	0.097	0.116	0.081	0.101	0.091	0.103	0.079	0.019
LEVEL-3 STDEV				0.044	0.037	0.051	0.045	0.047	0.050	0.052	0.055

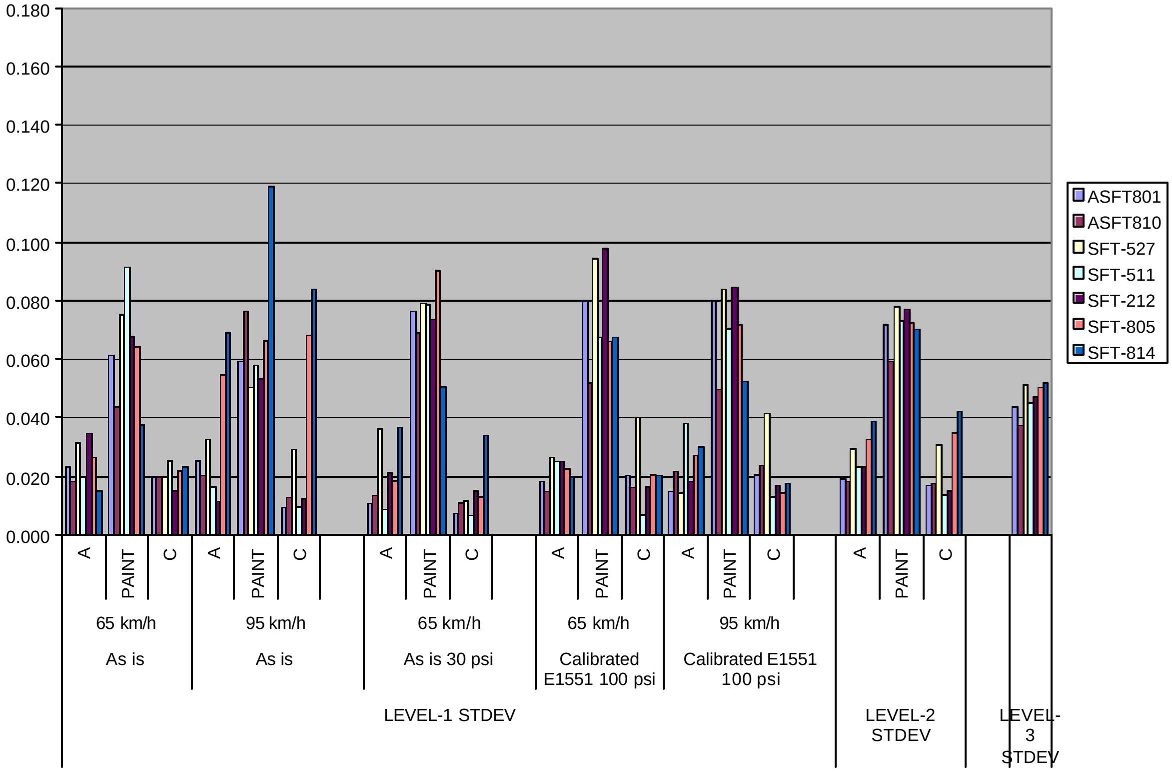


Figure 61. Level-1, Level-2 and Level-3 standard deviation for each device

The pooled total standard deviation for the device can then be used to calculate the total repeatability uncertainty for each individual device and for each individual measurement session consisting of several runs. The procedure for the calculation is given in section 5.4, equation (8). Using the mathematical procedures, the unmitigated repeatability standard deviation of each device for the different measurement sessions was calculated. The tabulated data is shown in Table 10.

Table 10. Level-3 repeatability uncertainty for each individual device and for each individual measurement session

			ASFT-801	ASFT-810	SFT-527	SFT-511	SFT-212	SFT-805	SFT-814	BV-11
As is	65 km/h	A	0.052	0.044	0.065	0.053	0.061	0.063	0.064	0.057
		PAINT	0.097	0.077	0.112	0.117	0.105	0.102	0.089	0.118
		C	0.050	0.044	0.061	0.053	0.051	0.063	0.068	0.056
As is	95 km/h	A	0.053	0.045	0.066	0.052	0.053	0.078	0.090	0.056
		PAINT	0.096	0.097	0.099	0.097	0.098	0.103	0.139	0.110
		C	0.047	0.042	0.065	0.048	0.051	0.088	0.102	0.057
As is 30 psi	65 km/h	A	0.048	0.042	0.067	0.051	0.056	0.061	0.072	0.056
		PAINT	0.106	0.092	0.115	0.109	0.109	0.119	0.095	0.134
		C	0.048	0.042	0.059	0.050	0.054	0.059	0.070	0.056
Calibrated E1551 100 psi	65 km/h	A	0.050	0.043	0.063	0.055	0.057	0.062	0.065	0.057
		PAINT	0.109	0.081	0.125	0.102	0.125	0.103	0.104	0.139
		C	0.050	0.043	0.070	0.047	0.052	0.062	0.067	0.056
Calibrated E1551 100 psi	95 km/h	A	0.049	0.046	0.059	0.061	0.055	0.063	0.069	0.060
		PAINT	0.109	0.080	0.118	0.104	0.116	0.106	0.096	0.129
		C	0.051	0.046	0.070	0.048	0.052	0.061	0.067	0.059

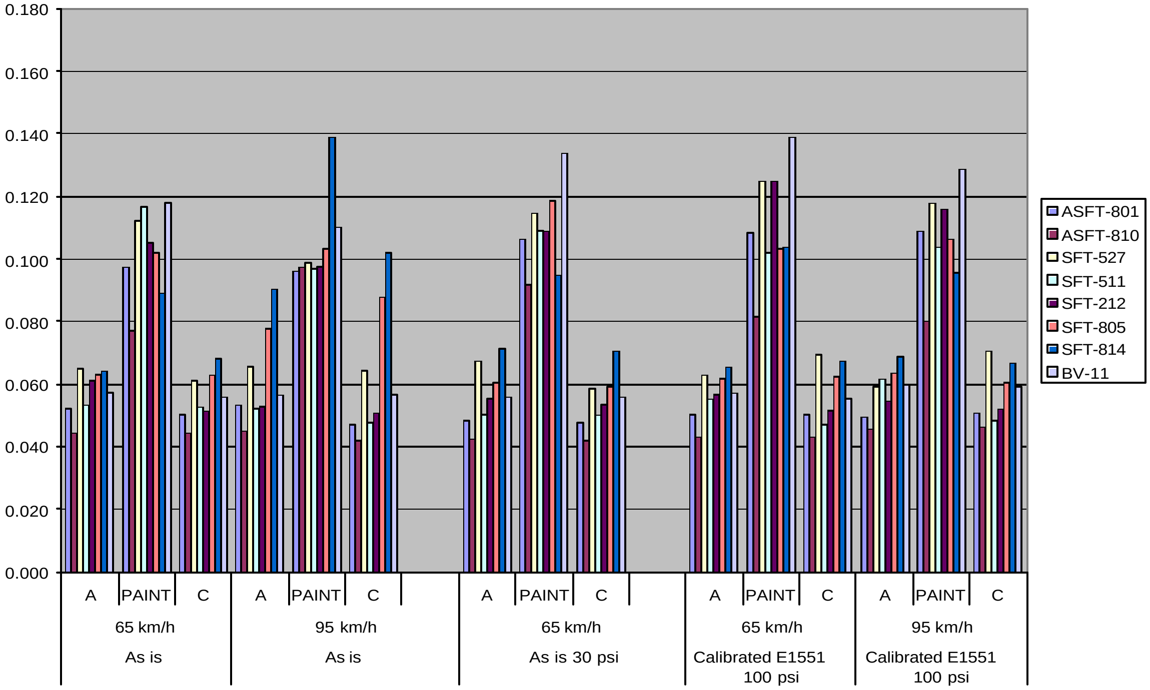


Figure 62. Level-3 repeatability uncertainty for each individual device and for each individual measurement session

The repeatability standard deviations in Table 10 were used to pool the parameters for the entire test for each device to produce the average Level-3 repeatability uncertainty of each individual device. These statistical values are the true measure of uncertainty of the devices without regard of speed and nominal friction value. The calculated values are shown in Figure 63.

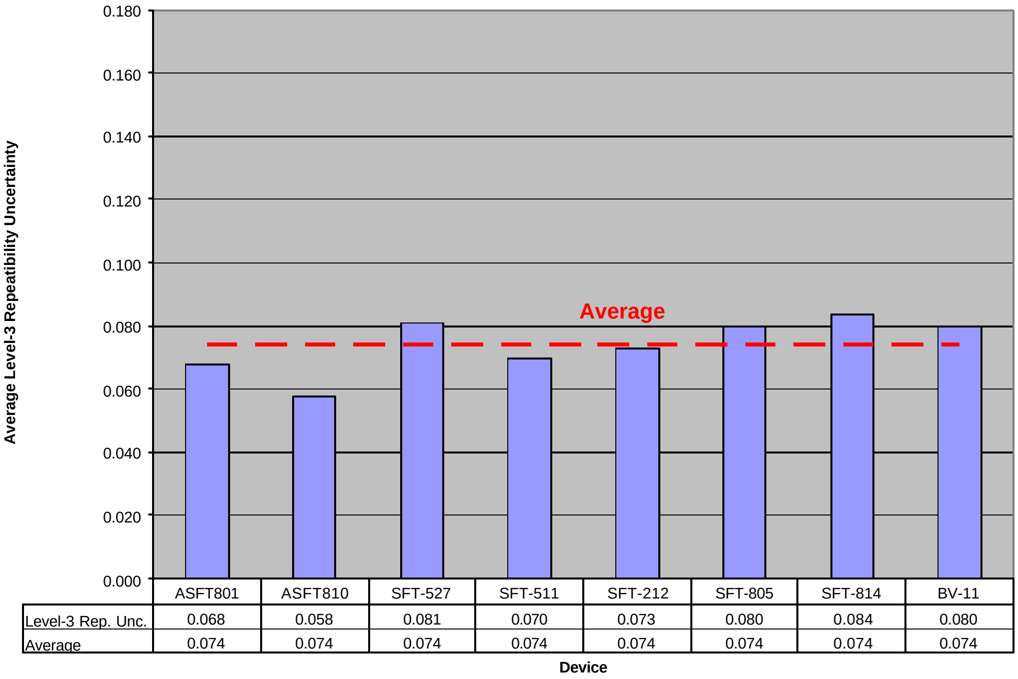


Figure 63. Average Level-3 repeatability uncertainty for each participating device

This figure shows that the average repeatability uncertainty among the SAAB family of friction measuring devices is 0.07.

The calculated coefficients of variation and standard error statistics are shown in Table 11 and Table 12. These statistical parameters are useful to assess uncertainty in repeated measurements that does not bare inferences about the overall repeatability of the device. It is included here for compatibility.

Table 11. Coefficient of variations for the different measurement sessions, speeds and surfaces

			ASFT-801	ASFT-810	SFT-527	SFT-511	SFT-212	SFT-805	SFT-814	BV-11
As is	65 km/h	A	3%	3%	4%	2%	4%	3%	2%	2%
		PAINT	12%	8%	14%	16%	14%	11%	7%	13%
		C	3%	3%	3%	3%	2%	3%	3%	1%
As is	95 km/h	A	4%	3%	5%	2%	2%	7%	9%	2%
		PAINT	13%	16%	14%	14%	16%	15%	29%	13%
		C	1%	2%	4%	1%	2%	9%	11%	2%

As is 30 psi	65 km/h	A	1%	2%	5%	1%	3%	2%	4%	1%
		PAINT	15%	12%	15%	13%	14%	17%	10%	20%
		C	1%	1%	1%	1%	2%	2%	4%	1%
Calibrated E1551 100 psi	65 km/h	A	3%	2%	3%	3%	3%	3%	2%	2%
		PAINT	22%	12%	20%	13%	19%	19%	13%	21%
		C	3%	2%	5%	1%	2%	3%	2%	1%
Calibrated E1551 100 psi	95 km/h	A	3%	4%	2%	6%	3%	4%	4%	3%
		PAINT	28%	16%	24%	24%	23%	27%	16%	20%
		C	4%	4%	6%	2%	3%	3%	3%	3%

The calculated average coefficients of variations are shown in Figure 64.

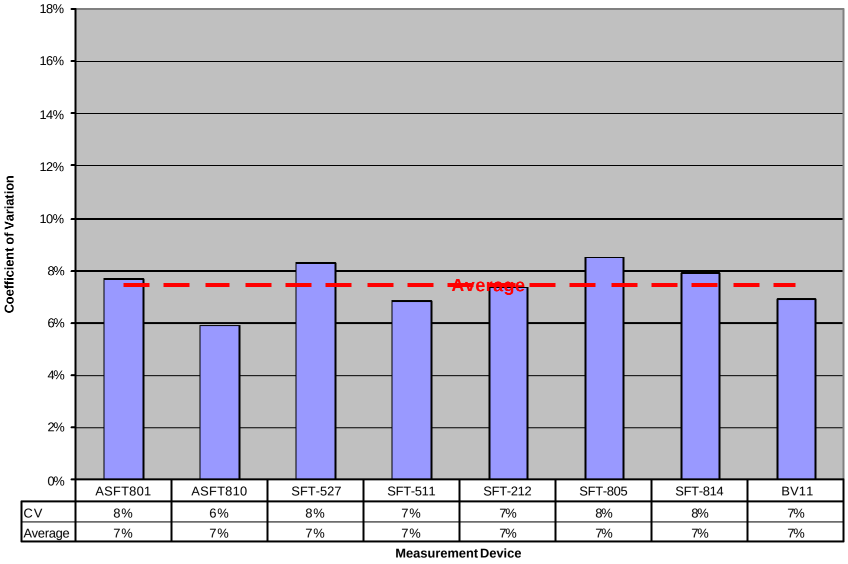


Figure 64. Averaged coefficient of variations for each participating device

This figure shows that the average coefficient of variation among the SAAB family of friction measuring devices is 7%.

Table 12. Standard error for the different measurement sessions, speeds and surfaces

			ASFT-801	ASFT-810	SFT-527	SFT-511	SFT-212	SFT-805	SFT-814	BV11
As is	65 km/h	A	0.007	0.006	0.010	0.007	0.011	0.008	0.005	0.006
		PAINT	0.019	0.014	0.024	0.032	0.021	0.020	0.012	0.023
		C	0.006	0.006	0.007	0.009	0.005	0.007	0.007	0.004
As is	95 km/h	A	0.008	0.006	0.010	0.005	0.004	0.017	0.023	0.004
		PAINT	0.019	0.024	0.016	0.018	0.017	0.021	0.040	0.019
		C	0.003	0.004	0.009	0.003	0.004	0.022	0.028	0.005

As is 30 psi	**65 km/h**	A	0.003	0.004	0.011	0.003	0.007	0.006	0.012	0.003
		PAINT	0.024	0.023	0.025	0.025	0.023	0.029	0.016	0.031
		C	0.002	0.004	0.004	0.002	0.005	0.004	0.011	0.003
Calibrated E1551 100 psi	**65 km/h**	A	0.006	0.005	0.008	0.008	0.008	0.007	0.006	0.005
		PAINT	0.025	0.016	0.030	0.021	0.031	0.021	0.021	0.034
		C	0.006	0.005	0.013	0.002	0.005	0.007	0.006	0.004
Calibrated E1551 100 psi	**95 km/h**	A	0.005	0.007	0.005	0.013	0.006	0.010	0.010	0.008
		PAINT	0.025	0.016	0.027	0.024	0.027	0.025	0.017	0.029
		C	0.007	0.007	0.013	0.004	0.005	0.005	0.006	0.008

The calculated average standard errors are shown in Figure 65.

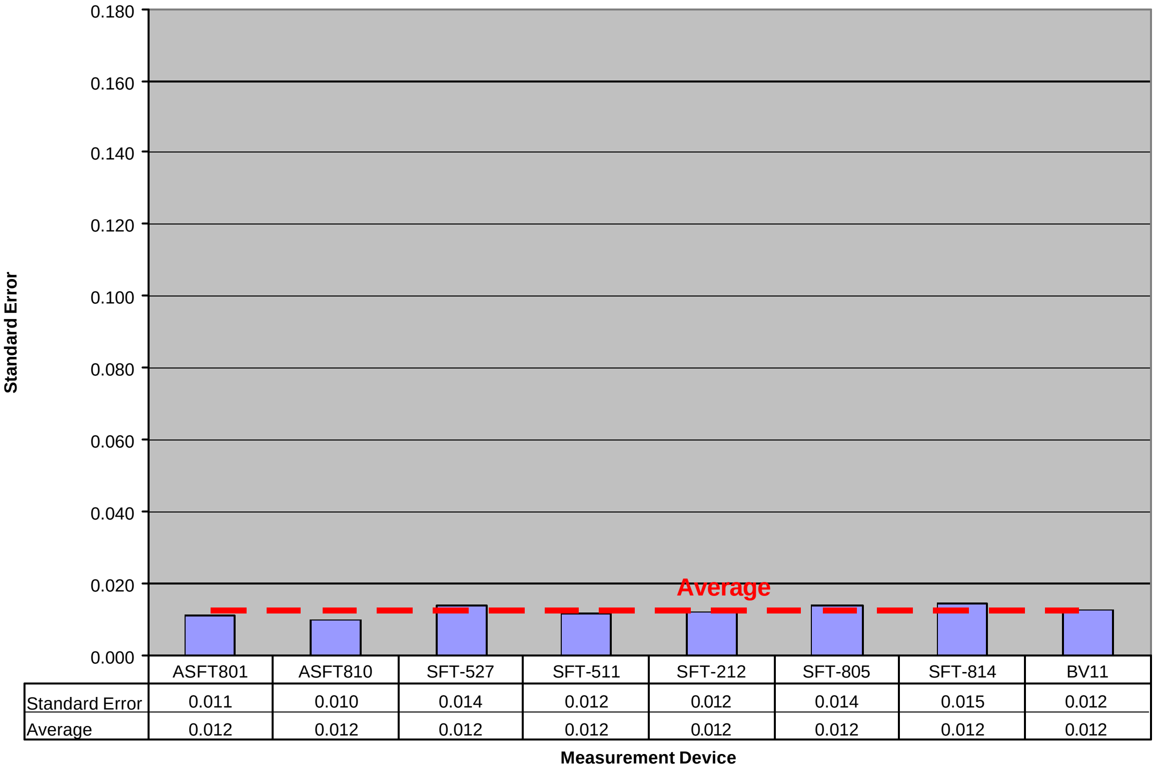


Figure 65. Averaged standard error for each participating device

This figure shows that the average standard error among the SAAB family of friction measuring devices is 0.01.

8.2 Reproducibility statistics

The mathematical procedures described in 5.5.2 were used with the reformulated Level-1, Level-2 and Level-3 standard deviations to calculate the reproducibility statistics of the measurement equipment family.

The calculated reproducibility standard deviations for the Level-1, Level-2 and Level-3 statistics are shown in tabulated format in Table 13 and Table 14.

Table 13. Calculated reproducibility standard deviations

		Level-1 Reproducibility Standard Deviation									
		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10
As is 65 km/h	**A**	0.075	0.073	0.072	0.079	0.058	0.076	0.049	0.066	0.067	0.062
	Paint	0.031	0.086	0.064	0.066	0.081	0.037	0.048	0.068	0.074	0.085
	C	0.042	0.037	0.030	0.020	0.025	0.038	0.040	0.035	0.026	0.041
As is 95 km/h	**A**	0.075	0.077	0.093	0.078	0.047	0.052	0.064	0.106	0.091	0.058
	Paint	0.086	0.107	0.076	0.081	0.073	0.069	0.077	0.073	0.091	0.070
	C	0.053	0.060	0.073	0.058	0.053	0.055	0.042	0.093	0.070	0.050
As is 65 km/h 30 psi	**A**	0.043	0.067	0.045	0.047	0.034	0.029	0.033	0.034	0.045	0.057
	Paint	0.095	0.058	0.095	0.074	0.079	0.069	0.100	0.075	0.081	0.059
	C	0.040	0.045	0.040	0.038	0.032	0.040	0.039	0.039	0.047	0.045
Calibrated condition 65 km/h ASTM1551 100 psi	**A**	0.094	0.092	0.089	0.100	0.082	0.075	0.090	0.088	0.085	0.081
	Paint	0.087	0.137	0.121	0.114	0.135	0.102	0.100	0.083	0.061	0.082
	C	0.080	0.080	0.071	0.084	0.055	0.057	0.061	0.066	0.059	0.073
Calibrated condition 95 km/h ASTM1551 100 psi	**A**	0.066	0.064	0.054	0.060	0.062	0.067	0.046	0.059	0.066	0.060
	Paint	0.067	0.075	0.054	0.081	0.070	0.121	0.075	0.032	0.088	0.073
	C	0.055	0.051	0.046	0.041	0.073	0.057	0.044	0.039	0.044	0.032

Table 14. Calculated reproducibility standard deviations (cont.)

		Level-2 Reproducibility Standard Deviation
As is 65 km/h	A	0.013
	Paint	0.030
	C	0.007
As is 95 km/h	A	0.013
	Paint	0.031
	C	0.016
As is 65 km/h 30 psi	A	0.013
	Paint	0.027
	C	0.011
Calibrated condition 65 km/h ASTM1551 100 psi	A	0.017
	Paint	0.028
	C	0.014
Calibrated condition 95 km/h ASTM1551 100 psi	A	0.017
	Paint	0.030
	C	0.014

	Level-3 Reproducibility Standard Deviation
A	0.069
Paint	0.083
C	0.053

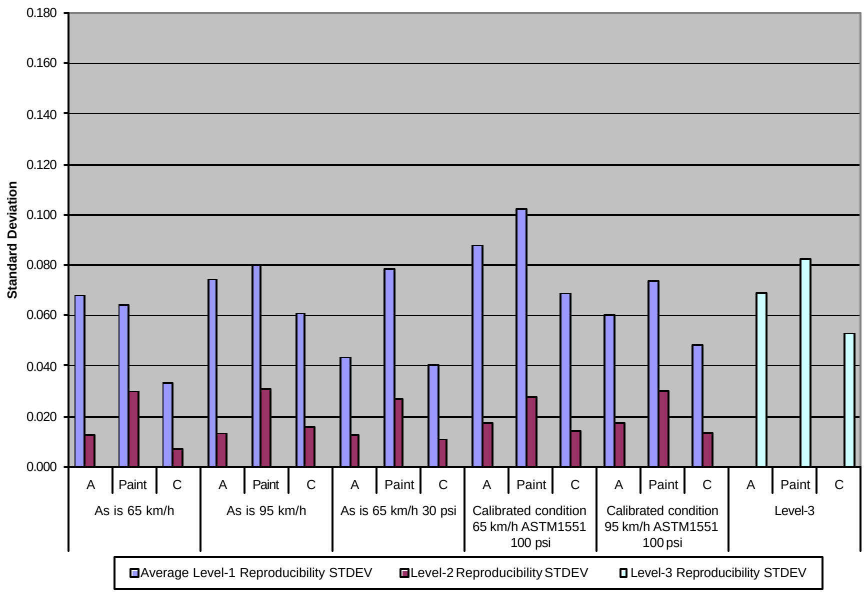


Figure 66. Level-1, Level-2 and Level-3 reproducibility standard deviation

The pooled Level-1, Level-2 and Level-3 standard deviation for each measuring session can be used to calculate the total reproducibility uncertainty for each measuring session. The procedure for the calculation is given in section 5.4, equation (8).

Table 15. Total reproducibility uncertainty

		Total Reproducibility Uncertainty									
		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10
As is 65 km/h	**A**	**0.112**	**0.110**	**0.110**	**0.115**	**0.099**	**0.113**	**0.092**	**0.104**	**0.106**	**0.101**
	Paint	**0.105**	**0.137**	**0.122**	**0.124**	**0.134**	**0.107**	**0.113**	**0.125**	**0.129**	**0.137**
	C	**0.087**	**0.085**	**0.081**	**0.077**	**0.079**	**0.085**	**0.086**	**0.084**	**0.079**	**0.087**
As is 95 km/h	**A**	**0.112**	**0.166**	**0.175**	**0.166**	**0.151**	**0.153**	**0.158**	**0.184**	**0.174**	**0.155**
	Paint	**0.138**	**0.239**	**0.224**	**0.227**	**0.223**	**0.222**	**0.225**	**0.223**	**0.231**	**0.222**
	C	**0.105**	**0.171**	**0.177**	**0.171**	**0.168**	**0.169**	**0.164**	**0.189**	**0.176**	**0.167**
As is 65 km/h 30 psi	**A**	**0.088**	**0.158**	**0.148**	**0.149**	**0.144**	**0.143**	**0.144**	**0.144**	**0.148**	**0.153**
	Paint	**0.144**	**0.207**	**0.223**	**0.213**	**0.215**	**0.211**	**0.226**	**0.214**	**0.216**	**0.207**
	C	**0.097**	**0.147**	**0.145**	**0.145**	**0.143**	**0.145**	**0.145**	**0.145**	**0.148**	**0.147**
Calibrated condition 65 km/h ASTM1551 100 psi	**A**	**0.106**	**0.173**	**0.171**	**0.178**	**0.167**	**0.162**	**0.171**	**0.170**	**0.168**	**0.166**
	Paint	**0.125**	**0.244**	**0.233**	**0.228**	**0.243**	**0.221**	**0.220**	**0.211**	**0.202**	**0.211**
	C	**0.130**	**0.181**	**0.176**	**0.183**	**0.169**	**0.170**	**0.172**	**0.174**	**0.170**	**0.177**
Calibrated condition 95 km/h ASTM1551 100 psi	**A**	**0.076**	**0.074**	**0.064**	**0.070**	**0.072**	**0.077**	**0.055**	**0.069**	**0.076**	**0.070**
	Paint	**0.109**	**0.116**	**0.099**	**0.121**	**0.112**	**0.157**	**0.116**	**0.087**	**0.126**	**0.114**
	C	**0.113**	**0.111**	**0.108**	**0.105**	**0.125**	**0.114**	**0.107**	**0.104**	**0.107**	**0.101**

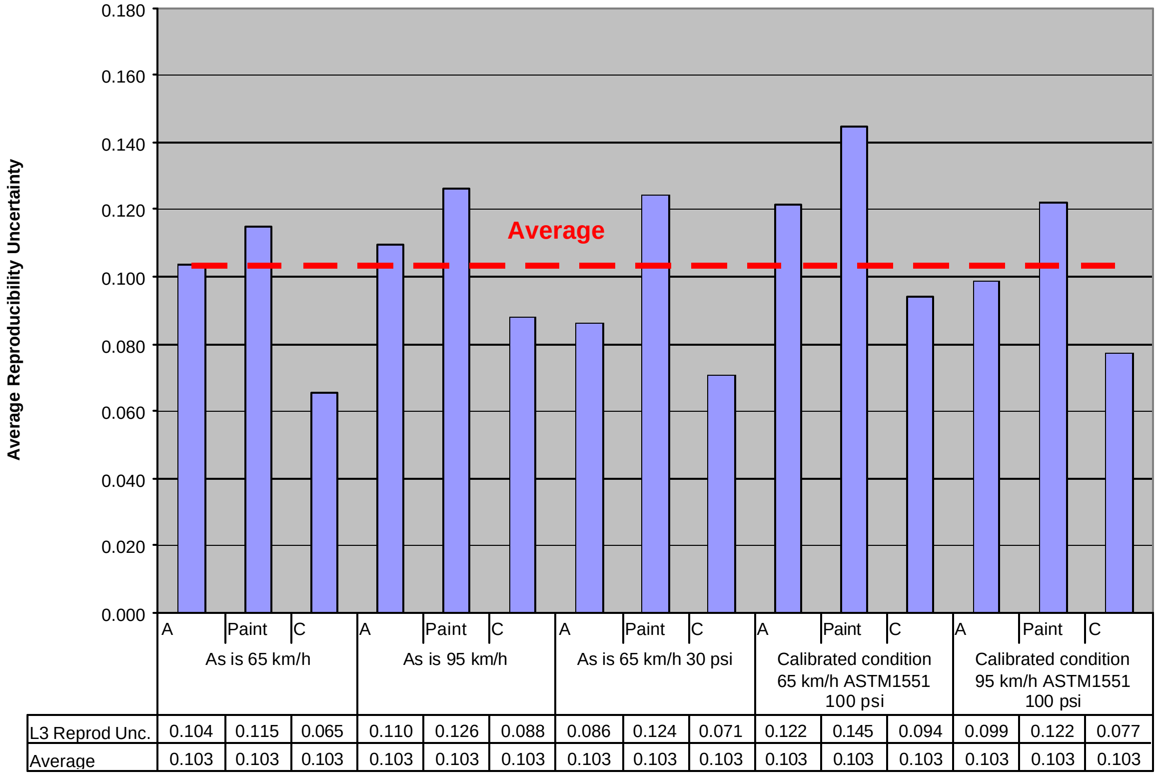


Figure 67. Average reproducibility uncertainty

This figure shows that the average reproducibility uncertainty for the SAAB family of friction measuring devices is 0.1.

The coefficient of variation for the different runs in the waves for the reproducibility analysis was calculated. The data in tabulated format is shown in Table 16.

Table 16. Calculated coefficient of variation for reproducibility analysis

		CV									
		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10
As is 65 km/h	**A**	**10%**	**9%**	**9%**	**10%**	**7%**	**10%**	**6%**	**8%**	**8%**	**8%**
	Paint	**5%**	**16%**	**12%**	**14%**	**16%**	**7%**	**9%**	**13%**	**14%**	**16%**
	C	**5%**	**5%**	**4%**	**2%**	**3%**	**5%**	**5%**	**4%**	**3%**	**5%**
As is 95 km/h	**A**	**10%**	**10%**	**12%**	**11%**	**7%**	**7%**	**9%**	**14%**	**13%**	**8%**
	Paint	**20%**	**26%**	**19%**	**21%**	**19%**	**16%**	**19%**	**15%**	**21%**	**18%**
	C	**7%**	**8%**	**10%**	**8%**	**8%**	**8%**	**6%**	**12%**	**10%**	**7%**
As is 65 km/h 30 psi	**A**	**5%**	**8%**	**5%**	**6%**	**4%**	**3%**	**4%**	**4%**	**5%**	**7%**
	Paint	**19%**	**10%**	**17%**	**14%**	**15%**	**12%**	**20%**	**15%**	**14%**	**10%**
	C	**5%**	**5%**	**5%**	**5%**	**4%**	**5%**	**5%**	**5%**	**5%**	**5%**

Calibrated condition 65 km/h ASTM1551 100 psi	**A**	12%	12%	11%	13%	11%	10%	12%	12%	11%	11%
	Paint	20%	29%	27%	25%	26%	23%	23%	17%	14%	18%
	C	10%	10%	9%	11%	7%	7%	8%	9%	8%	10%
Calibrated condition 95 km/h ASTM1551 100 psi	**A**	10%	10%	8%	9%	10%	10%	7%	10%	10%	9%
	Paint	18%	26%	19%	25%	20%	40%	24%	10%	30%	26%
	C	9%	8%	7%	7%	11%	9%	7%	7%	7%	5%

The calculated average reproducibility coefficient of variations are shown in Figure 68.

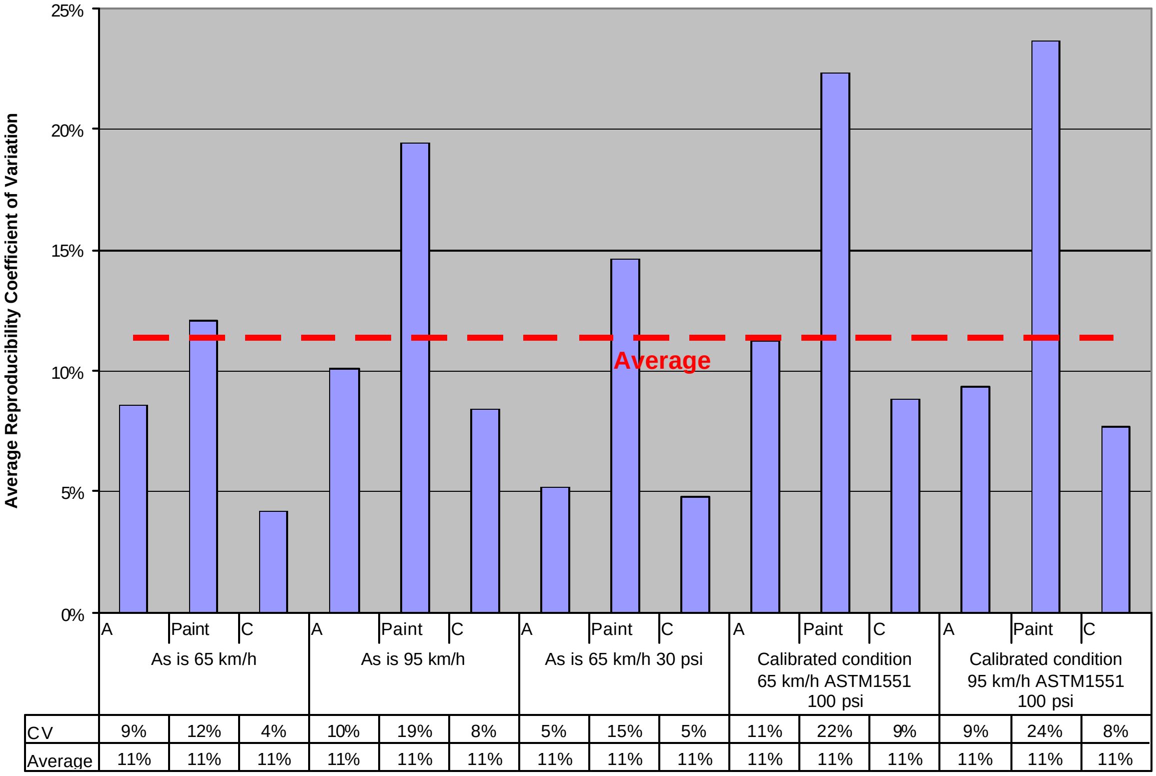


Figure 68. Average reproducibility coefficient of variations

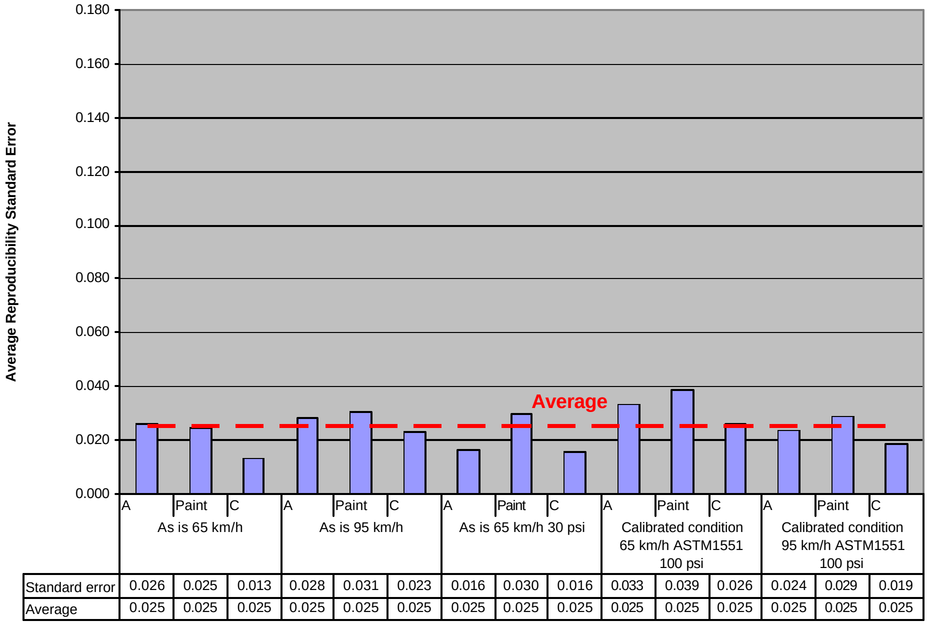
This figure shows that the average reproducibility coefficient of variation for the SAAB family of friction measuring devices is 11%.

The standard error for each run was also calculated and tabulated. The parameters are shown in Table 17.

Table 17. Calculated standard errors for reproducibility analysis

		Standard Error									
		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10
As is 65 km/h	A	0.028	0.027	0.027	0.030	0.022	0.029	0.020	0.029	0.025	0.023
	Paint	0.012	0.032	0.024	0.025	0.031	0.014	0.020	0.028	0.028	0.032
	C	0.016	0.014	0.012	0.007	0.009	0.014	0.016	0.014	0.010	0.016
As is 95 km/h	A	0.029	0.031	0.035	0.029	0.018	0.020	0.024	0.040	0.035	0.022
	Paint	0.032	0.043	0.029	0.031	0.028	0.026	0.029	0.027	0.034	0.026
	C	0.020	0.024	0.027	0.022	0.020	0.021	0.016	0.035	0.026	0.019
As is 65 km/h 30 psi	A	0.016	0.025	0.017	0.018	0.014	0.011	0.012	0.013	0.017	0.021
	Paint	0.036	0.022	0.036	0.028	0.032	0.026	0.038	0.028	0.031	0.022
	C	0.016	0.017	0.015	0.015	0.013	0.015	0.015	0.015	0.019	0.017
Calibrated condition 65 km/h ASTM1551 100 psi	A	0.035	0.035	0.034	0.038	0.031	0.028	0.034	0.033	0.032	0.031
	Paint	0.033	0.052	0.046	0.043	0.051	0.039	0.038	0.031	0.023	0.031
	C	0.030	0.030	0.027	0.032	0.021	0.022	0.023	0.025	0.022	0.028
Calibrated condition 95 km/h ASTM1551 100 psi	A	0.025	0.026	0.021	0.023	0.025	0.027	0.017	0.022	0.025	0.024
	Paint	0.025	0.031	0.020	0.031	0.027	0.049	0.028	0.012	0.033	0.030
	C	0.021	0.021	0.018	0.016	0.027	0.023	0.017	0.015	0.017	0.013

The calculated average reproducibility standard errors are shown in Figure 69.



	As is 65 km/h A	As is 65 km/h Paint	As is 65 km/h C	As is 95 km/h A	As is 95 km/h Paint	As is 95 km/h C	As is 65 km/h 30 psi A	As is 65 km/h 30 psi Paint	As is 65 km/h 30 psi C	Calibrated condition 65 km/h ASTM1551 100 psi A	Calibrated condition 65 km/h ASTM1551 100 psi Paint	Calibrated condition 65 km/h ASTM1551 100 psi C	Calibrated condition 95 km/h ASTM1551 100 psi A	Calibrated condition 95 km/h ASTM1551 100 psi Paint	Calibrated condition 95 km/h ASTM1551 100 psi C
Standard error	0.026	0.025	0.013	0.028	0.031	0.023	0.016	0.030	0.016	0.033	0.039	0.026	0.024	0.029	0.019
Average	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025

Figure 69. Average reproducibility standard error

This figure shows that the average reproducibility standard error for the SAAB family of friction measuring devices is 0.02.

A combined graphical view of the repeatability of the different measurement devices is shown in Figure 70 through Figure 72.

The figures show the individual bell-shaped curves of the repeatability Level-2 standard deviations of each device for the three different surfaces (A, PAINT and C) in relation to each other for better understanding. The scale on the lower axes is maintained throughout the three figures for better comparison.

The individual bell-shaped curves in each figure are labelled with the corresponding device designation. The curves are shown in vertical offset to place them in the same figure; this prevents showing the actual vertical scale. However, the qualitative understanding of the figure will not suffer from this since the information of the figure itself is the different curve shapes in relation to one another and the location or offset of the individual curves from the overall means.

The two outside vertical lines on the graphs are placed to the absolute minima and maxima of the averages of the measurement devices. The centre vertical line indicates the calculated averages calculated from the means of the individual devices.

The distribution of the bell-shaped curves along the horizontal axis indicates the repeatability standard deviations of the SAAB friction measurement device type.

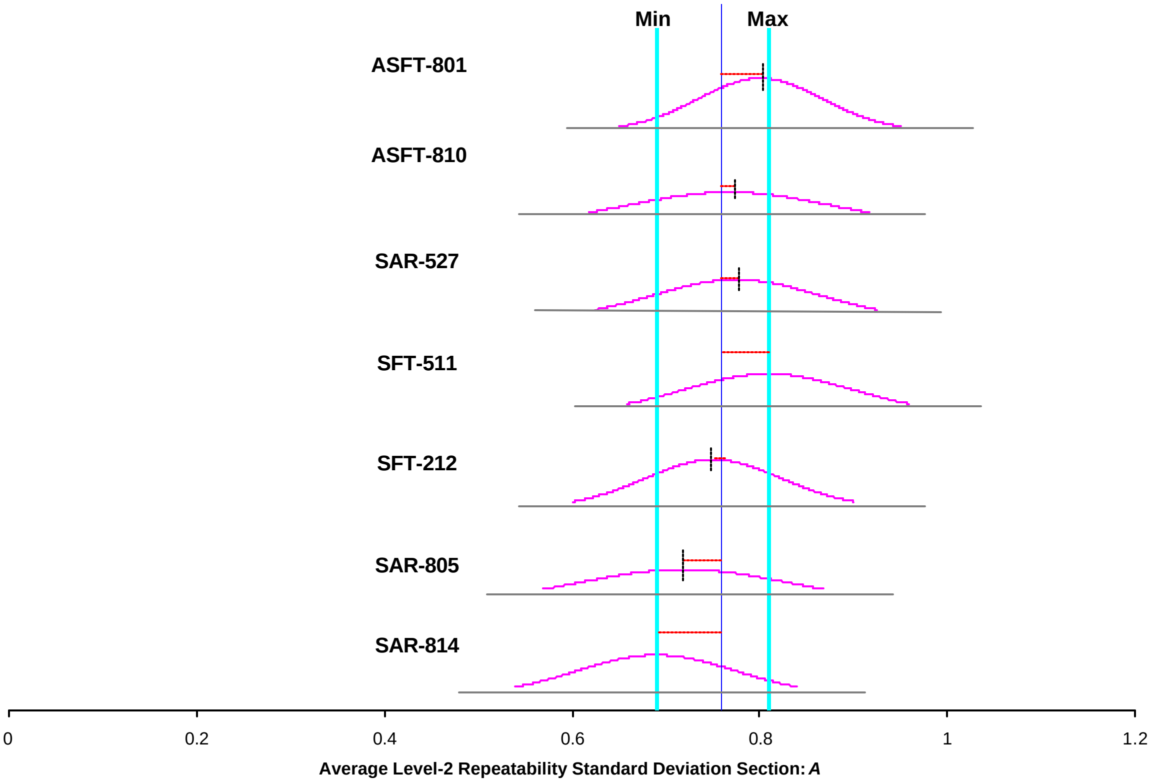


Figure 70. Level-2 repeatability standard deviation section: A

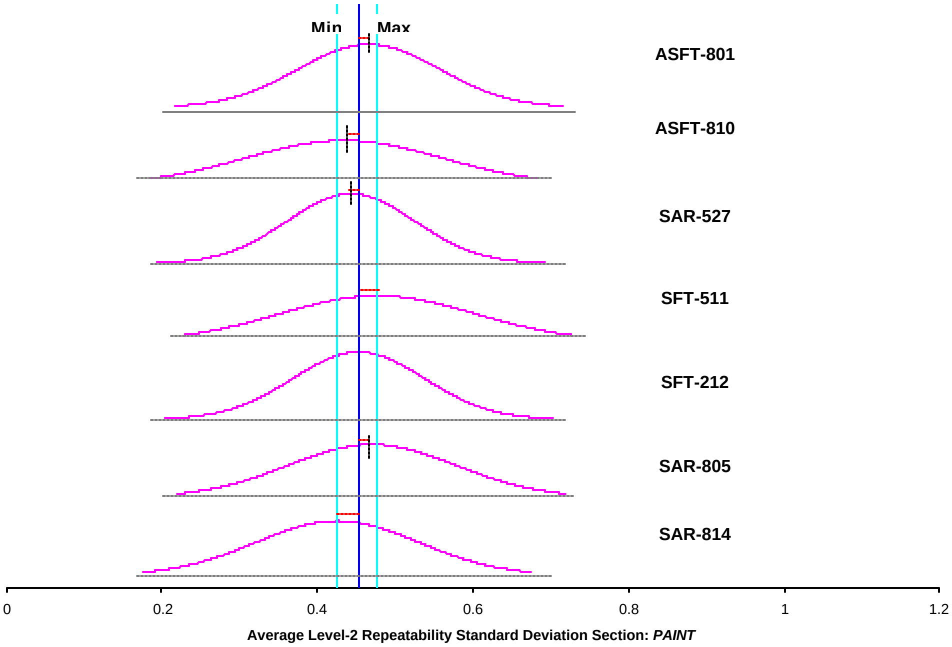


Figure 71. Level-2 repeatability standard deviation section: PAINT

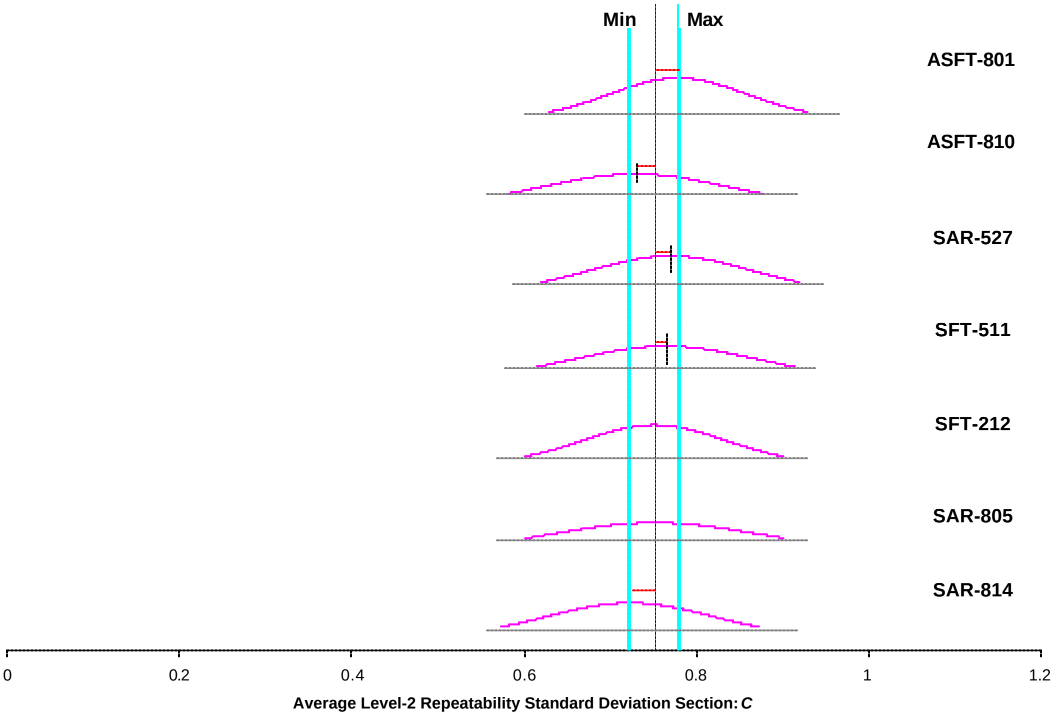


Figure 72. Level-2 repeatability standard deviation section: C

9 CONCLUSIONS

The measurement of friction coefficient is a physical phenomenon where the reference values must be consensus-based values in the absence of any traceable physical or international standard, where the reference is based on measurements made according to a specific protocol by a group of laboratories. This specific protocol was not available at the time of the preparation of this report and therefore, with no calibration reference available, bias cannot be established for the analyzed friction measurement devices.

The overall description of the measurement device reproducibility is the maximum uncertainty standard deviation. This is the maximum of the calculated Level-3 reproducibility uncertainty (Figure 67), which for the Saab family (in these tests) of friction measurement device is **0.14** with an average uncertainty of **0.10**.

This means that the uncertainty of the Saab family of friction measurement devices for a measurement made in self-wet mode is **0.10** friction units on a scale of 0.0 to 1.0, with a maximum uncertainty deviation of **0.14**.

It was determined that the repeatability of the participating Saab friction measurement devices in self-wet mode produced an uncertainty of **0.07** average repeatability standard deviation friction units on a scale of 0 to 1.00, with a maximum uncertainty deviation of **0.08** and the minimum uncertainty **0.06** (Figure 63). Thus, the uncertainty content of the Saab friction measurement units as a whole under self-wet conditions is an average of **7%** of the maximum scale.

Relating the variability with the friction level by using the coefficient of variation provides compatibility of this study to other repeatability studies. The average repeatability coefficient of variation for all devices and surfaces combined was **6.6%** and the corresponding average reproducibility coefficient of variation was **11.4%** (Figure 64 and Figure 68).

The original scope of the test was to conduct measurements on numerous different surfaces, mainly winter surfaces, but due to mild weather it was not possible. Accordingly, the measurements analyzed in this report were made on a limited selection of surfaces. Therefore, these results should be used with careful consideration as a general evaluation for the participating measuring device.

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APPENDIX A

The Complete Data Set

As is 65 km/h

		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10	Average	STD	N
ASFT801-sft	A	0.65	0.69	0.71	0.68	0.72	0.71	0.73	0.71	0.70	0.72	0.70	0.023	10
	Paint	0.55	0.45	0.45	0.55	0.55	0.58	0.55	0.52	0.57	0.40	0.52	0.061	10
	C	0.73	0.73	0.74	0.78	0.77	0.76	0.78	0.77	0.78	0.76	0.76	0.020	10
ASFT810-sft	A	0.69	0.74	0.72	0.70	0.72	0.75	0.72	0.73	0.72	0.74	0.72	0.018	10
	Paint	0.59	0.61	0.61	0.55	0.57	0.53	0.50	0.53	0.48	0.55	0.55	0.044	10
	C	0.75	0.75	0.78	0.77	0.79	0.78	0.73	0.76	0.79	0.77	0.77	0.019	10
FAA212-sft	A	0.74	0.80	0.80	0.84	0.83	0.84	0.83	0.85	0.86	0.83	0.82	0.035	10
	Paint	0.58	0.47	0.51	0.39	0.37	0.51	0.45	0.55	0.43	0.51	0.48	0.068	10
	C	0.80	0.81	0.80	0.81	0.80	0.83	0.83	0.82	0.84	0.80	0.81	0.015	10
PRA511-sft	A	0.82	0.86	0.88	0.87	0.86	0.88			0.86	0.88	0.86	0.020	8
	Paint	0.64	0.65	0.64	0.40	0.46	0.59			0.56	0.60	0.57	0.091	8
	C	0.78	0.80	0.80	0.81	0.82	0.86			0.84	0.83	0.82	0.025	8
FRK527-sft	A	0.75	0.74	0.76	0.79	0.80	0.70	0.78	0.77	0.80	0.74	0.76	0.032	10
	Paint	0.59	0.46	0.55	0.45	0.57	0.56	0.55	0.41	0.60	0.65	0.54	0.075	10
	C	0.78	0.82	OL:0.9	0.80	0.78	0.77	0.82	0.82	0.80	0.78	0.80	0.020	9
ARL805-sft	A	0.85	0.88	0.89	0.87	0.84	0.87	0.83	0.85	0.86	0.80	0.85	0.026	10
	Paint	0.60	0.62	0.51	0.50	0.60	0.60	0.59	0.62	0.65	0.45	0.57	0.064	10
	C	0.80	0.78	0.82	0.82	0.84	0.83	0.82	0.78	0.78	0.80	0.81	0.022	10
STR814-sft	A	0.83	0.85	0.83	0.84	0.84	0.84	0.81	OL:0.93	0.81	0.85	0.83	0.015	9
	Paint	0.55	0.58	0.55	0.51	0.48	0.61	0.52	0.54	0.52	0.51	0.54	0.038	10
	C	0.86	0.83	0.82	0.82	0.82	0.83	0.83	0.85	0.80	0.88	0.83	0.023	10
AVERAGE	A	0.76	0.79	0.80	0.80	0.80	0.80	0.78	0.78	0.80	0.79			10
	Paint	0.59	0.55	0.55	0.48	0.51	0.57	0.53	0.53	0.54	0.52			10
	C	0.79	0.79	0.79	0.80	0.80	0.81	0.80	0.80	0.80	0.80			10
Level-1 STD	A	0.075	0.073	0.072	0.079	0.058	0.076	0.049	0.066	0.067	0.062			10
	Paint	0.031	0.086	0.064	0.066	0.081	0.037	0.048	0.068	0.074	0.085			10
	C	0.042	0.037	0.030	0.020	0.025	0.038	0.040	0.035	0.026	0.041			10

As is 95 km/h

		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10	Average	STD	N
ASFT801-sft	A	0.68	0.7	0.67	0.69	0.68	0.64	0.7	0.68	0.62	0.67	0.67	0.025	10
	Paint	0.5	0.55	0.4	0.38	0.48	0.4	0.52	0.42	0.45	0.4	0.45	0.059	10
	C	0.75	0.74	0.74	0.74	0.72	0.74	0.75	0.74	0.73	0.73	0.74	0.009	10
ASFT810-sft	A	0.76	0.76	0.74	0.74	0.73	0.72	0.7	0.75	0.72	0.76	0.74	0.020	10
	Paint	0.55	0.55	0.45	0.55	0.4	0.52	0.45	0.55	0.4	0.35	0.48	0.076	10
	C	0.78	0.76	0.78	0.77	0.78	0.79	0.8	0.8	0.78	0.77	0.78	0.013	10
FAA212-sft	A	0.71	0.68	0.7	0.67	0.69	0.7	0.69	0.7	0.69	0.7	0.69	0.012	10
	Paint	0.31	0.35	0.4	0.41	0.29	0.33	0.35	0.43	0.31	0.27	0.35	0.054	10
	C	0.69	0.68	0.68	0.66	0.66	0.67	0.68	0.7	0.68	0.68	0.68	0.012	10
PRA511-sft	A	0.79	0.76	0.75	0.74	0.74	0.76	0.76	0.77	0.74	0.74	0.76	0.016	10
	Paint	0.38	0.31	0.4	0.4	0.34	0.47	0.46	0.43	0.48	0.35	0.40	0.058	10
	C	0.71	0.7	0.68	0.69	0.69	0.7	0.7	0.71	0.69	0.69	0.70	0.010	10
FRK527-sft	A	0.67	0.7	0.65	0.64	0.66	0.68	0.63	0.59	0.62	0.62	0.65	0.033	10
	Paint	0.37	0.36	0.31	0.32	0.43	0.35	0.38	0.45	0.32	0.43	0.37	0.050	10
	C	0.67	0.67	0.65	0.62	0.62	0.62	0.7	0.65	0.66	0.61	0.65	0.029	10
ARL805-sft	A	0.89	0.89	0.93	0.88	0.8	0.8	0.83	0.79	0.8	0.77	0.84	0.055	10
	Paint	0.4	0.37	0.51	0.31	0.45	0.45	0.4	0.5	0.5	0.49	0.44	0.066	10
	C	0.82	0.83	0.86	0.78	0.72	0.73	0.69	0.7	0.67	0.69	0.75	0.068	10
STR814-sft	A	0.75		0.77	0.74	0.74	0.73	0.75	0.93	0.87	0.77	0.78	0.069	9
	Paint	0.49		0.29	0.35	0.31	0.47	0.29	0.61	0.55	0.37	0.41	0.119	9
	C	0.71		0.7	0.71	0.74	0.74	0.71	0.93	0.85	0.67	0.75	0.084	9
AVERAGE	A	0.75	0.75	0.74	0.73	0.72	0.72	0.72	0.74	0.72	0.72			10
	Paint	0.43	0.42	0.39	0.39	0.39	0.43	0.41	0.48	0.43	0.38			10
	C	0.73	0.73	0.73	0.71	0.70	0.71	0.72	0.75	0.72	0.69			10
Level-1 STD	A	0.075	0.077	0.093	0.078	0.047	0.052	0.064	0.106	0.091	0.058			10
	Paint	0.086	0.107	0.076	0.081	0.073	0.069	0.077	0.073	0.091	0.070			10
	C	0.053	0.060	0.073	0.058	0.053	0.055	0.042	0.093	0.070	0.050			10

As is 65 km/h 30 psi

		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10	Average	STD	N
ASFT801-sft	**A**	0.82	0.81	0.83	0.8	0.82	0.82	0.82	0.8	0.83	0.82	**0.82**	**0.011**	**10**
	Paint	0.42	0.62	0.49	0.5	0.62	0.5	0.5	0.42	0.62	0.54	**0.52**	**0.076**	**10**
	C	OL:0.76	0.84	0.85	0.83	0.85	0.85	0.84	0.84	0.85	0.85	**0.84**	**0.007**	**9**
ASFT810-sft	**A**	0.87	0.87	0.87	0.87		0.86	0.88	0.86	0.89	0.9	**0.87**	**0.013**	**9**
	Paint	0.5	0.58	0.6	0.52		0.68	0.5	0.62	0.52	0.66	**0.58**	**0.069**	**9**
	C	0.89	0.9	0.91	0.91		0.91	0.91	0.89	0.92	0.92	**0.91**	**0.011**	**9**
FAA212-sft	**A**	0.87	0.85	0.86	0.85	0.84	0.83	0.82	0.82	0.88	0.87	**0.85**	**0.021**	**10**
	Paint	0.41	0.5	0.66	0.51	0.51	0.52	0.5	0.45	0.62	0.48	**0.52**	**0.074**	**10**
	C	0.87	0.86	0.86	0.84	0.84	0.86	0.85	0.85	0.89	0.87	**0.86**	**0.015**	**10**
PRA511-sft	**A**	0.89	0.9	0.89	0.89	0.88	0.88	0.88	0.88	0.9	0.9	**0.89**	**0.009**	**10**
	Paint	0.65	0.5	0.65	0.65	0.63	0.63	0.69	0.45	0.65	0.54	**0.60**	**0.079**	**10**
	C	0.87	0.87	0.86	0.87	0.87	0.87	0.86	0.86	OL:0.90	0.88	**0.87**	**0.007**	**9**
FRK527-sft	**A**	0.76	0.69	0.75	0.75	0.79	0.8	0.81	0.79	0.79	0.74	**0.77**	**0.036**	**10**
	Paint	0.42	0.61	0.49	0.62	0.45	0.51	0.41	0.58	0.5	0.6	**0.52**	**0.079**	**10**
	C	0.78	0.76	0.78	0.79	0.78	0.8	0.8	0.78	0.79	0.78	**0.78**	**0.012**	**10**
ARL805-sft	**A**	0.85	0.83	0.84	0.82	0.79	0.85	0.83	0.82	0.83	0.85	**0.83**	**0.019**	**10**
	Paint	0.6	0.6	0.4	0.48	0.53	0.61	0.4	0.5	0.65	0.61	**0.54**	**0.090**	**10**
	C	0.85	0.81	0.82	0.83	0.83	0.83	0.82	0.82	0.85	0.82	**0.83**	**0.013**	**10**
STR814-sft	**A**	0.84	0.84	0.84	0.81	0.81	0.81	0.8	0.8	0.91	0.88	**0.83**	**0.037**	**10**
	Paint	0.52	0.49	0.56	0.45	0.45	0.55	0.58	0.55	0.45	0.55	**0.52**	**0.051**	**10**
	C	0.82	0.83	0.83	0.82	0.81	0.8	0.8	0.79	0.9	0.87	**0.83**	**0.034**	**10**
AVERAGE	**A**	**0.84**	**0.83**	**0.84**	**0.83**	**0.82**	**0.84**	**0.83**	**0.82**	**0.86**	**0.85**			**10**
	Paint	**0.50**	**0.56**	**0.55**	**0.53**	**0.53**	**0.57**	**0.51**	**0.51**	**0.57**	**0.57**			**10**
	C	**0.85**	**0.84**	**0.84**	**0.84**	**0.83**	**0.85**	**0.84**	**0.83**	**0.87**	**0.86**			**10**
Level-1 STD	**A**	**0.043**	**0.067**	**0.045**	**0.047**	**0.034**	**0.029**	**0.033**	**0.034**	**0.045**	**0.057**			**10**
	Paint	**0.095**	**0.058**	**0.095**	**0.074**	**0.079**	**0.069**	**0.100**	**0.075**	**0.081**	**0.059**			**10**
	C	**0.040**	**0.045**	**0.040**	**0.038**	**0.032**	**0.040**	**0.039**	**0.039**	**0.047**	**0.045**			**10**

Calibrated condition 65 km/h ASTM1551 100 psi

		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10	Average	STD	N
ASFT801-sft	A	0.7	0.7	0.68	0.65	0.67	0.69	0.68	0.66	0.68	0.65	0.68	0.018	10
	Paint	0.3	0.3	0.25	0.3	0.35	0.5	0.3	0.41	0.42	0.43	0.36	0.080	10
	C	0.73	0.69	0.69	0.68	0.71	0.73	0.72	0.68	0.71	0.68	0.70	0.020	10
ASFT810-sft	A	0.7	0.7	0.68	0.68	0.7	0.69	0.68	0.66	0.68	0.66	0.68	0.015	10
	Paint	0.42	0.45	0.5	0.41	0.55	0.39	0.39	0.42	0.42	0.48	0.44	0.052	10
	C	0.71	0.74	0.73	0.71	0.74	0.72	0.74	0.7	0.73	0.7	0.72	0.016	10
FAA212-sft	A	0.9	0.86	0.86	0.84	0.83	0.82	0.85	0.82	0.84	0.82	0.84	0.025	10
	Paint	0.38	0.6	0.55	0.45	0.62	0.58	0.59	0.57	0.4	0.38	0.51	0.098	10
	C	0.86	0.85	0.85	0.84	0.83	0.82	0.83	0.81	0.82	0.82	0.83	0.016	10
PRA511-sft	A	0.89	0.88	0.87	0.86	0.86	0.83	0.87	0.83	0.86	0.81	0.86	0.025	10
	Paint	0.5	0.6	0.47	0.52	0.59	0.51	0.41	0.5	0.43	0.6	0.51	0.067	10
	C	0.82	0.83	0.82	0.82	0.81	0.81	0.81	0.81	0.82	0.81	0.82	0.007	10
FRK527-sft	A	0.86	0.89	0.84	0.89	0.85	0.83	0.81	0.83	0.84	0.83	0.85	0.026	10
	Paint	0.45	0.45	0.61	0.56	0.62	0.39	0.41	0.54	0.36	0.41	0.48	0.095	10
	C	0.9	0.89	0.82	0.89	0.81	0.81	0.81	0.82	0.81	0.8	0.84	0.040	10
ARL805-sft	A	0.74	0.71	0.71	0.71	0.72	0.69	0.68	0.66	0.7	0.72	0.70	0.023	10
	Paint	0.5	0.29	0.35	0.32	0.3	0.27	0.4	0.36	0.38	0.35	0.35	0.066	10
	C	0.72	0.71	0.69	0.69	0.71	0.68	0.67	0.7	0.69	0.65	0.69	0.021	10
STR814-sft	A	0.89	0.87	0.85	0.86	0.85	0.84	0.85	0.82	0.84	0.83	0.85	0.020	10
	Paint	0.56	0.6	0.45	0.59	0.6	0.42	0.55	0.56	0.55	0.45	0.53	0.067	10
	C	0.87	0.86	0.84	0.83	0.83	0.81	0.82	0.82	0.82	0.81	0.83	0.020	10
AVERAGE	A	0.81	0.80	0.78	0.78	0.78	0.77	0.77	0.75	0.78	0.76			10
	Paint	0.44	0.47	0.45	0.45	0.52	0.44	0.44	0.48	0.42	0.44			10
	C	0.80	0.80	0.78	0.78	0.78	0.77	0.77	0.76	0.77	0.75			10
Level-1 STD	A	0.094	0.092	0.089	0.100	0.082	0.075	0.090	0.088	0.085	0.081			10
	Paint	0.087	0.137	0.121	0.114	0.135	0.102	0.100	0.083	0.061	0.082			10
	C	0.080	0.080	0.071	0.084	0.055	0.057	0.061	0.066	0.059	0.073			10

		Calibrated condition 95 km/h ASTM1551 100 psi										Average	STD	N
		Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10			
ASFT801-sft	**A**	0.59	0.57	0.61	0.59	0.57	0.57	0.59	0.56	0.57	0.58	**0.58**	**0.015**	**10**
	Paint	0.25	0.23	0.32	0.32	0.39	0.15	0.19	0.35	0.37	0.25	**0.28**	**0.080**	**10**
	C	0.57	0.56	0.57	0.59	0.57	0.59	0.6	0.55	0.62	0.57	**0.58**	**0.021**	**10**
ASFT810-sft	**A**	0.59	0.57	0.6	0.55	0.58	0.56	0.58	0.54	0.61	0.57	**0.58**	**0.022**	**10**
	Paint	0.35	0.35	0.27	0.27	0.24	0.29	0.35	0.38	0.28	0.25	**0.30**	**0.050**	**10**
	C	0.6	0.57	0.6	0.56	0.59	0.57	0.58	0.55	0.63	0.6	**0.59**	**0.024**	**10**
FAA212-sft	**A**	0.71	0.66	0.67	0.66	0.66	0.66	0.67	0.64	0.68	0.66	**0.67**	**0.018**	**10**
	Paint	0.45	0.25	0.34	0.48	0.45	0.26	0.38	0.31	0.3	0.43	**0.37**	**0.084**	**10**
	C	0.7	0.66	0.67	0.66	0.68	0.66	0.67	0.64	0.68	0.65	**0.67**	**0.017**	**10**
PRA511-sft	**A**	0.71		0.7	0.64	0.7	0.67	0.66	0.63	0.75	0.66	**0.68**	**0.038**	**9**
	Paint	0.37		0.23	0.38	0.35	0.25	0.37	0.31	0.2	0.24	**0.30**	**0.071**	**9**
	C	0.62		0.62	0.62	0.63	0.62	0.62	0.6	0.65	0.62	**0.62**	**0.013**	**9**
FRK527-sft	**A**	0.73	0.73	0.73	0.73	OL:0.82	0.72	0.7	0.69	0.72	0.72	**0.72**	**0.015**	**9**
	Paint	0.4	0.33	0.31	0.23	0.4	0.5	0.39	0.31	0.43	0.25	**0.36**	**0.084**	**10**
	C	0.68	0.66	0.68	0.66	0.78	0.72	0.68	0.64	0.68	0.64	**0.68**	**0.042**	**10**
ARL805-sft	**A**	0.65	0.62	0.62	0.59	0.63		0.61	0.56	0.6		**0.61**	**0.027**	**8**
	Paint	0.34	0.2	0.19	0.34	0.29		0.25	0.35	0.18		**0.27**	**0.072**	**8**
	C	0.57	0.56	0.57	0.58	0.59		0.56	0.59	0.55		**0.57**	**0.015**	**8**
STR814-sft	**A**	0.75	0.68	0.72	0.66	0.72	0.7	0.67	0.67	0.66	0.69	**0.69**	**0.030**	**10**
	Paint	0.43	0.39	0.3	0.3	0.35	0.38	0.3	0.29	0.28	0.29	**0.33**	**0.053**	**10**
	C	0.68	0.65	0.66	0.65	0.66	0.68	0.63	0.63	0.64	0.65	**0.65**	**0.018**	**10**
AVERAGE	**A**	**0.68**	**0.64**	**0.66**	**0.63**	**0.64**	**0.65**	**0.64**	**0.61**	**0.66**	**0.65**			**10**
	Paint	**0.37**	**0.29**	**0.28**	**0.33**	**0.35**	**0.31**	**0.32**	**0.33**	**0.29**	**0.29**			**10**
	C	**0.63**	**0.61**	**0.62**	**0.62**	**0.64**	**0.64**	**0.62**	**0.60**	**0.64**	**0.62**			**10**
Level-1 STD	**A**	**0.066**	**0.064**	**0.054**	**0.060**	**0.062**	**0.067**	**0.046**	**0.059**	**0.066**	**0.060**			**10**
	Paint	**0.067**	**0.075**	**0.054**	**0.081**	**0.070**	**0.121**	**0.075**	**0.032**	**0.088**	**0.073**			**10**
	C	**0.055**	**0.051**	**0.046**	**0.041**	**0.073**	**0.057**	**0.044**	**0.039**	**0.044**	**0.032**			**10**