

CERTIFICATION PROCESS FOR SELF-WETTING CONTINUOUS FRICTION-MEASURING EQUIPMENT USED FOR CONSTRUCTION AND MAINTENANCE PURPOSES ON FRENCH AIRPORTS

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ABSTRACT

Friction characteristics of runways are regularly measured to detect any change in skid resistance and to decide maintenance needs. Self-wetting continuous friction measuring equipments (CFME) are used for functional (construction and maintenance) measurements. Numerous friction measuring devices exist and are currently used on airports. These devices have different functioning principles: operating modes, water delivery systems, measuring tires types and pressures... It causes friction characteristics of runway to be both surface- and device-dependant. Many attempts have been made to correlate friction measuring devices with each other and good results have been achieved for functional friction measurements. Harmonization of friction measurements makes it possible to define minimum friction levels. Below these friction levels, corrective actions have to be taken to improve runway friction characteristics, and pilots have to be informed of such conditions. To achieve this, France has introduced a regulation to submit CFME to mandatory certification.

This paper presents the certification process for self-wetting continuous friction measuring equipments used for functional measurements on French airports. Certification ensures aerodrome operators that CFME performs with reliability and consistency. It also harmonizes friction measurements between different devices and ensures a uniform acceptance of the minimum friction level.

The certification process consists in correlation trials between the applicant device and the reference device, owned by the French Civil Aviation Technical Center (STAC). A special test track has been built on the grounds of Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR ex-LCPC). It has 11 differently textured test plots with surface properties covering a large range of friction levels.

The performances of all applicant devices in terms of repeatability and consistency of friction measurements are checked. A device meeting the requirements for certification is then correlated to the STAC reference device and is issued with a certificate valid for two years. All self-wetting continuous friction measuring devices used for construction and maintenance purposes on French airports have to be certified.

This process has proved to reduce significantly the variability of CFME friction results and progressively improved the overall consistency of applicant friction measurement devices. Examples of test results are presented and discussed in this paper.

1. INTRODUCTION

Runway friction significantly contributes to the security of aircraft operations. International standards require friction measurements on a regular basis to assess the evolution of runway friction characteristics, detect any change in friction characteristics and decide

maintenance actions. Friction measurements are performed using self-wetting continuous friction measuring equipment (CFME).

Numerous devices are currently commercialized and have different functioning principles: operating modes, water delivery systems, measuring tires, inflated tire pressures... It causes friction characteristics of runway to be both surface- and device-dependant. Device dependency is a major issue for the comparison of friction measurements and for the determination of the runway minimum friction level.

International correlation trials (ICAO programme for correlating equipment used in measuring runway braking action [1], Tire/Runway Friction Workshop at NASA WALLOPS flight facility [2], International PIARC Experiment [3] and Joint Winter Runway Friction Measurement Programme [4]) have been performed and have demonstrated that good correlation between different devices is achievable. Following the Joint Winter Runway Friction Measurement Programme, an international index, called International Runway Friction Index (IRFI), has been adopted. This index consists in a correlation of every device to a reference device ([5] and [6]). An ASTM standard [7] was published for the calculation of the IRFI. The main issue during those correlation trials has concerned the stability of the correlation in time. Indeed, it has been noticed that devices drifted and correlations needed to be re-actualized every year.

STAC has carried out a specific work to reduce the drift of the reference device and to reduce measurement uncertainties. Good results have been achieved concerning the stability of the correlation over periods of two years. Several years of certification tests have helped developing a national friction scale to which all equipments can report.

These results have allowed the French Civil Aviation Authority (DGAC) to produce rules concerning certification of self-wetting CFME used for construction and maintenance purposes. This paper is a presentation of the correlation trials performed for this certification process.

2. METHODOLOGY

French regulation requires every device used for construction and maintenance purposes to be certified by the State. Six types of device are currently recognized in France. These devices are presented in the table below:

Table 1 – Devices recognized by French DGAC

<i>Measuring device</i>	<i>Testing tire type</i>
Mumeter MK6	ASTM E670
Skiddometer BV11	ASTM E1551
SFT	ASTM E1551
RFT	ASTM E1551
SARSYS STFT	ASTM E1551
IMAG	PIARC

The certificate must be renewed every two years. Certification process consists in correlating a device to the reference device, and then studying the repeatability and the reproducibility of measurements.

2.1. The reference device

The reference device is a particular device chosen as a reference because its multiple participations to international correlation trials (Tire/Runway friction Workshop at NASA WALLOPS flight facility [2] and Joint Winter Runway Friction Measurement Programme [4]) showed it has a good repeatability and correlation with other CFME.

To minimize causes of deviations from one campaign to another, the reference device is:

- Well maintained and calibrated according to procedures set up by the STAC,
- Only used for certification of other devices,
- Coupled with its own towing vehicle and only used with that vehicle,
- Checked before and after every campaign.

Figure 1 shows the reference device with its coupled towing vehicle.



Figure 1 – The reference device with its coupled towing vehicle

2.2. Test facility

Certification tests are performed on specially prepared friction test track (figure 2) designed for testing, calibration and certification of surface characteristics (texture and friction) measuring equipments. It is divided into three sections:

- First section is a 1400 m long semi-circle is used for acceleration,
- Second section is 500 m long and includes the track zone with 11 test surfaces,
- Last section used for deceleration is 400 m long. .



Figure 2 – IFSTTAR test facility

2.3. Test surfaces

The friction track is constituted of 11 tests surfaces covering a large range of friction values. Disposition of test surfaces is presented in figure 3.

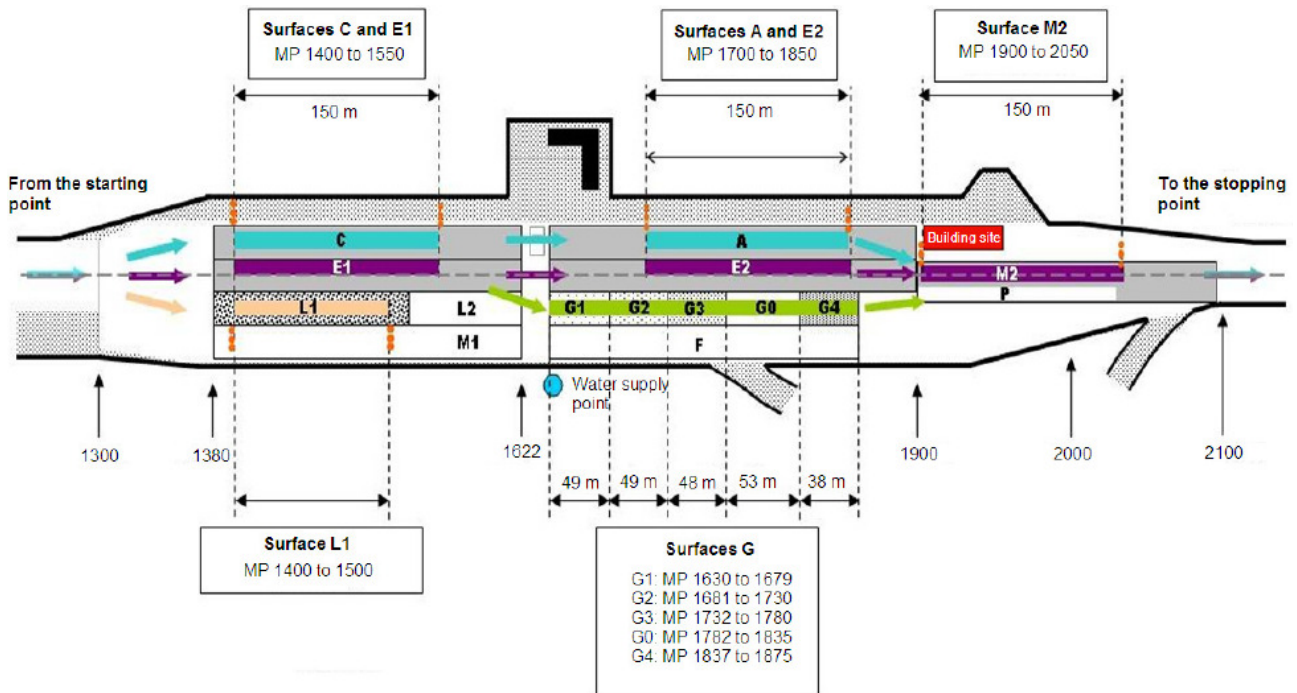


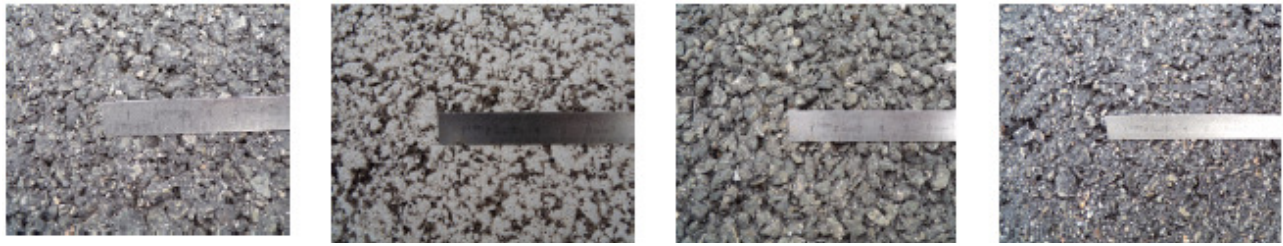
Figure 3 – Disposition of test surfaces

Surfaces A, E1, E2, and M2 are 150 m long and 2 m large and have medium to high friction levels. Surfaces G0 to G4 are 50 m long and 2 m large. Surfaces G1 to G4 have been painted in order to have low friction levels. Surface L1 is 100 m long and 2 m large. It is covered with epoxy and has very low friction values. The surface materials are detailed in table 2 below:

Table 2 - Surface materials

Test surface	Material	Range of friction values
A	Porous asphalt concrete (0/6)	From 0,58 at 95 km/h to 0,73 at 40 km/h
C	Surface dressing (0,8/1,5)	From 0,29 at 95 km/h to 0,82 at 40 km/h
E1	Semi-granular bituminous concrete (0/10)	From 0,33 at 95 km/h to 0,71 at 40 km/h
E2	Semi-granular bituminous concrete (0/10)	From 0,35 at 95 km/h to 0,59 at 40 km/h
G0	Low friction asphalt concrete	From 0,29 at 95 km/h to 0,70 at 40 km/h
G1	Slightly painted surface	From 0,12 at 95 km/h to 0,44 at 40 km/h
G2	Painted surface +	From 0,17 at 95 km/h to 0,44 at 40 km/h
G3	Painted surface ++	From 0,16 at 95 km/h to 0,55 at 40 km/h
G4	Painted surface +++	From 0,22 at 95 km/h to 0,67 at 40 km/h
L1	Epoxy	0,05 to 0,10
M2	Very thin bituminous concrete (0/6)	From 0,35 at 95 km/h to 0,65 at 40 km/h

Figure 4 shows pictures of some surfaces of the test track.



Surface E1

Surface G4

Surface M2

Surface G0

Figure 4 – Examples of test surfaces

Surfaces A and C are porous asphalt concrete and surface dressing. They have good macro-texture and do not show high friction values variation with speed. Therefore, it is generally not tested at high speed.

Surfaces G are painted surfaces and have poor micro- and macro-texture. They are generally tested at 65 km/h and 95 km/h to have low or very low friction levels. These surfaces generally give friction values around the minimum friction level of the reference device. Thus, they are of primary importance for the success of certification campaign. A sweeper is generally used to help water to run off these surfaces. It has proved to improve repeatability and avoid apparition of aquaplaning conditions. Results cannot be analyzed in aquaplaning conditions.

Surface L is covered with epoxy and presents very low friction values. It is generally used at 40 km/h because higher speeds lead to aquaplaning of the measuring wheel. It is usually used to check the offset of friction measuring equipments.

2.4. Testing methodology

A close attention is given to the testing methodology. As discussed later on, a friction measuring device is a complex measuring system and sources of uncertainties are various. It explains why two devices may have significantly different behaviors when used on the same surface, or why correlation constants may not be stable from one campaign to the other.

A specific study is being carried out by the STAC to determine sources of errors on friction measurements and to set tolerance levels on test parameters. This study has already demonstrated that tire wear is a significant parameter, since the difference between a new tire and a used tire may reach 0,10 friction unit (see part 4.4).

For the moment, participants are required to perform tests with a new and broken in (4 km) tire. The tolerance on testing speed is set at ± 5 km/h.

Friction measurements can be performed at the following speeds:

- 40, 65 and 95 km/h on all surfaces except L1
- 40 km/h on surface L1.

A repetition is defined as one run of one participant on one test surface. For each combination (participant, surface, speed), a minimum of five valid repetitions is required. Repetitions are needed to assess repeatability and reproducibility of the CFME.

The test operator is responsible for quality of measurements. Measurements can be done again until the operator judges it in accordance with its operating mode.

A test needs to be performed again:

- If the testing speed is not maintained within tolerances,
- If the participant veers off the centerline of the test surface,
- If the measuring wheel was in aquaplaning conditions,
- If any event happened during friction measurements made the test not conform to the operating mode of the participant,
- If there is any reason to question the measures.

3. RESULTS ANALYSIS

3.1. Data formatting and check

Test results analysis is based on friction coefficient measured during the certification campaign. Test data are formatted so as to pair data from the applicant device with data from the reference device. The pairing consists in joining data from both devices obtained in similar test conditions and over a short period of time.

First, all friction values are plotted, for both applicant and reference devices, against the speed and the test surface. It allows observing the range of individual values variation. Figure 5 is an example of plots obtained for one device. This device is called device XX in the whole paper, to illustrate the analysis process.

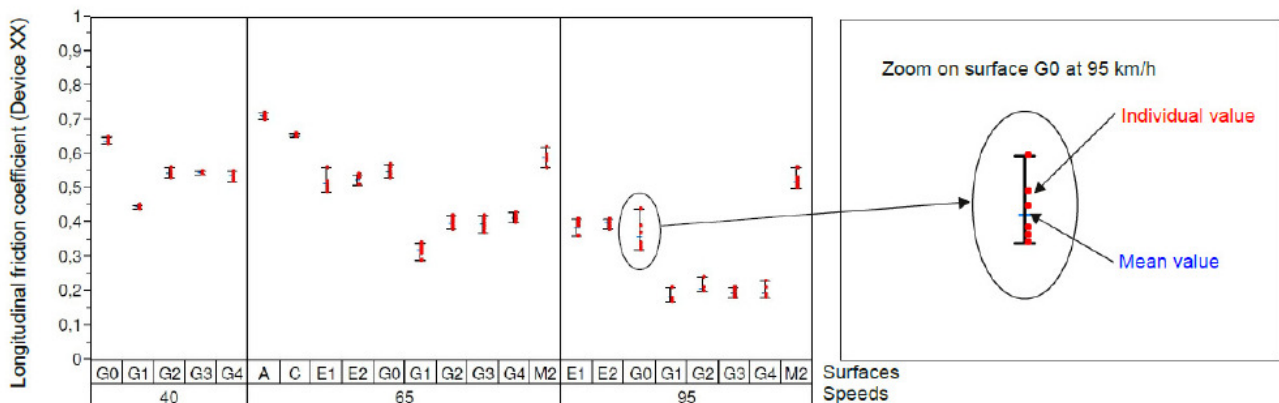


Figure 5 - Plots of individual friction values against speed and surface for device XX

Then, standard deviations are calculated for each device, speed and surface. The values are plotted along with the boundaries of their 95 % confidence interval, calculated by the Student law. A value of standard deviation out of these boundaries means that friction values for this test configuration show high variability compared to other test configurations. Friction values corresponding to this test configuration are identified for the next part of the analysis, but no value is removed at this stage of the analysis. Figure 6 is an example of standard deviations obtained for device XX.

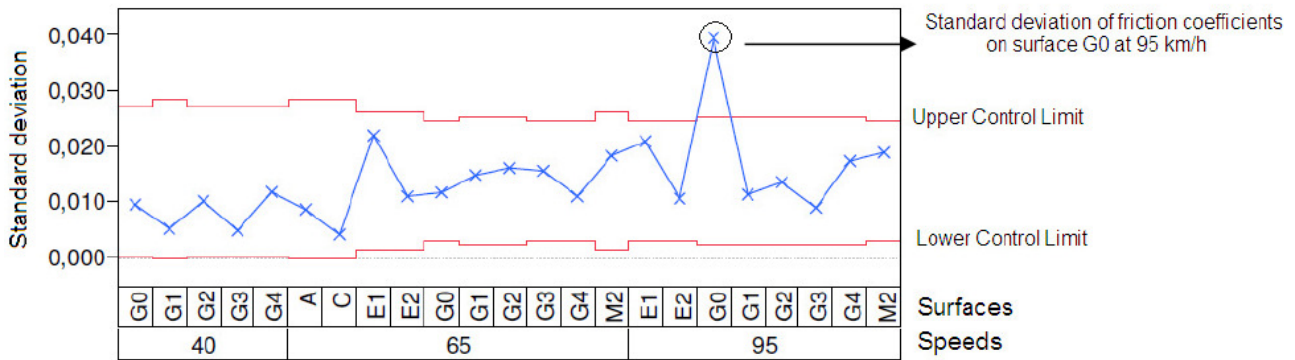


Figure 6 - Plots of standard deviations and boundaries of 95 % confidence interval against speeds and surfaces for device XX

3.2. Correlation

A simple linear regression ($Y=aX+b$) is performed on the whole data set. Data of the reference device are considered as the explanatory variable (X) and thus are plotted on the X-axis, while data of the applicant device are considered as the response variable (Y) and thus are plotted on the Y-axis.

The boundaries of the predicted values 95 % confidence interval are added to the graph. All values out of this interval are therefore considered as outliers and systematically removed from the data set for the rest of the analysis. These values may be caused by a non-controlled variation of one test parameter, the technology of the equipment, the surface characteristics or the meteorological conditions. No more than 5 % of the whole data set can be removed. This process is illustrated in figure 7.

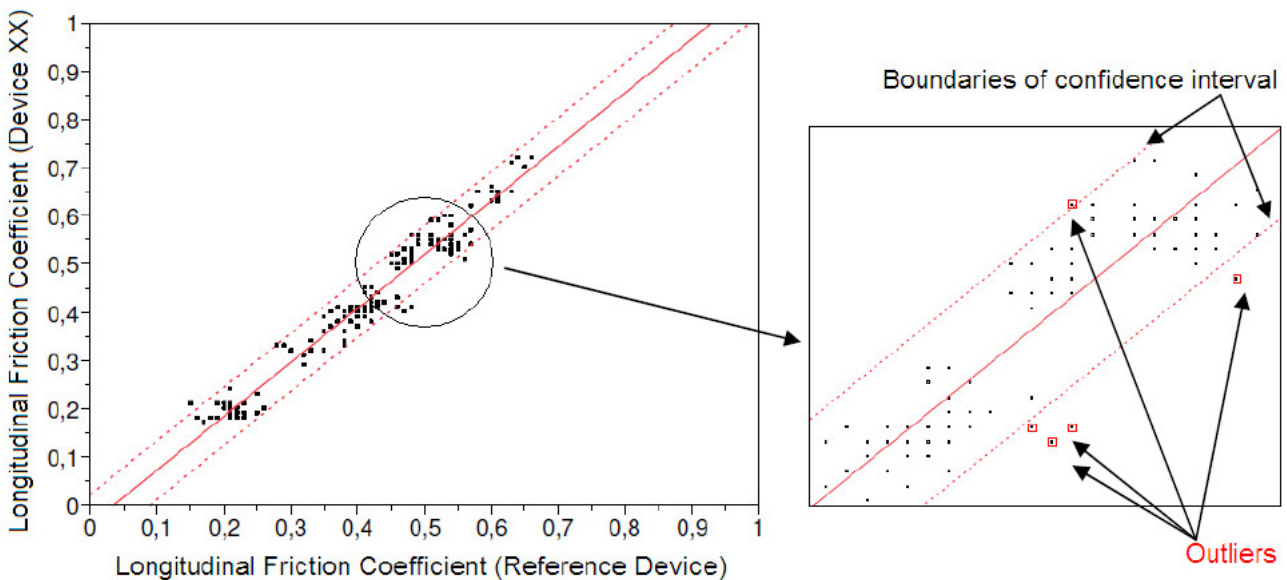


Figure 7 - Linear regression and identification of outlier values for device XX

Then, a new linear regression is calculated on the new data set (without outlier values). The coefficient of determination (R^2) is used to assess the quality of the relation between measurements. Graph of residuals is plotted to assess quality of the linear regression model.

Acceptable value for R^2 has been set to 0,90. This value means that 90 % of variability of applicant device friction values is explained by the variability of reference device friction values. If the R^2 criterion is not reached, a linear regression is determined per test speed.

In this case the acceptance criteria is “R² greater than 0,95”. If none of these criteria is reached, the device cannot be certified.

When one of these criteria is reached, a complementary analysis (part 3.3) is performed to check whether the correlation really improves the results provided by the device.

3.3. Repeatability and reproducibility analysis

The last part of the analysis process consists in a repeatability and reproducibility study of device measurements. Gauge R&r (repeatability and reproducibility) is applied. This method calculates the amount of variation due to the measuring system and compares it with the total variation observed. It determines the viability of the measurement system.

The regression is applied to individual values of the applicant device in order to relate them to the same scale as the reference device. Values of the applicant device can then be compared to values of the reference device.

Repeatability is calculated considering the repetitions of each device in every test configurations. Reproducibility is calculated taking into account the amount of variation due to the equipment and the amount of variation due to the interaction between the equipment and the test surface. These results relative to device XX at 95 km/h are presented in table 3.

Table 3 – Example of a gauge R&r results (Device XX at 95 km/h)

Sources	Standard deviation (σ)	Meaning
Repeatability	$1,77 \cdot 10^{-2}$	$\sigma^2(\text{Intra})$
Reproducibility	$8,97 \cdot 10^{-3}$	$\sigma^2(\text{Equipment}) + \sigma^2(\text{Equipment} * \text{Surface})$
Equipment	$3,04 \cdot 10^{-3}$	$\sigma^2(\text{Equipment})$
Equipment*Surface	$8,43 \cdot 10^{-3}$	$\sigma^2(\text{Interaction between equipment and surface})$
Repeatability and reproducibility (RR)	$1,99 \cdot 10^{-2}$	$\sigma^2(\text{Intra}) + \sigma^2(\text{Equipment}) + \sigma^2(\text{Equipment} * \text{Surface})$
Partial variation (PV)	$9,69 \cdot 10^{-2}$	$\sigma^2(\text{Surface})$
Total variation (TV)	$9,89 \cdot 10^{-2}$	$\sigma^2(\text{Intra}) + \sigma^2(\text{Equipment}) + \sigma^2(\text{Equipment} * \text{Surface}) + \sigma^2(\text{Surface})$

Gauge R&r is defined as the ratio between repeatability and reproducibility (RR) and total variation (TV). Acceptance criteria are summarized in table 4 below:

Table 4 – Acceptance criteria for R&r analysis

R&r value	Meaning	Conclusion
R&r \leq 30 %	Both devices are close in their behavior for the whole range of measured friction coefficients.	The device is acceptable.
R&r > 30 %	The applicant device has significantly different behavior against the levels of friction coefficients measured on the test surfaces.	The device is not capable of measuring.

Finally, the quality of the applied correlation is visually checked. Figure 8 shows applicant device correlated measurements and reference device measurements on every surface at

95 km/h. It shows that after correlation, both devices results are very close on each surface.

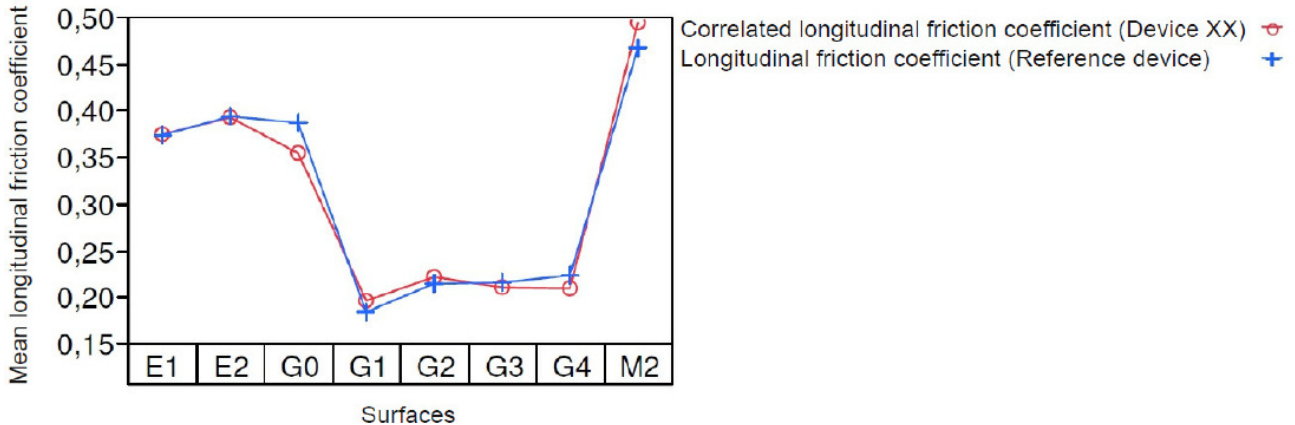


Figure 8 – Check of applied correlation for device XX at 95 km/h

4. DISCUSSION

This methodology has been implemented for the last 6 years. Over this period of time, 23 devices have been tested for certification, either for a first certification or a renewal. Only three devices have been refused.

A history of measures has been built for every certified device. These results show that this methodology reduces significantly variability of CFME friction results and improves reproducibility of friction measurements (part 4.1). Moreover, consistency of applicant device has been improved and it is now possible to keep harmonization constant stable from one campaign to another (part 4.2). Even better results would be obtained from a better control of measurement uncertainties, as discussed in part 4.4.

4.1. Reproducibility of friction measurements

One of the main concerns for airport operators is the device-dependency of friction measurements. Indeed, they have to be able to compare friction measurements between devices and to check that friction values are above regulatory minimum friction levels. A first benefit of the presented process is the harmonization of friction results for different devices.

Figure 9 shows results of one certification campaign. The observed maximal difference between two devices of different types was 0,26 friction unit. This difference after correlation, presented in figure 10, has been reduced at 0,09 friction unit. It proves the benefit of the correlation on reproducibility of friction measurements between devices of different types.

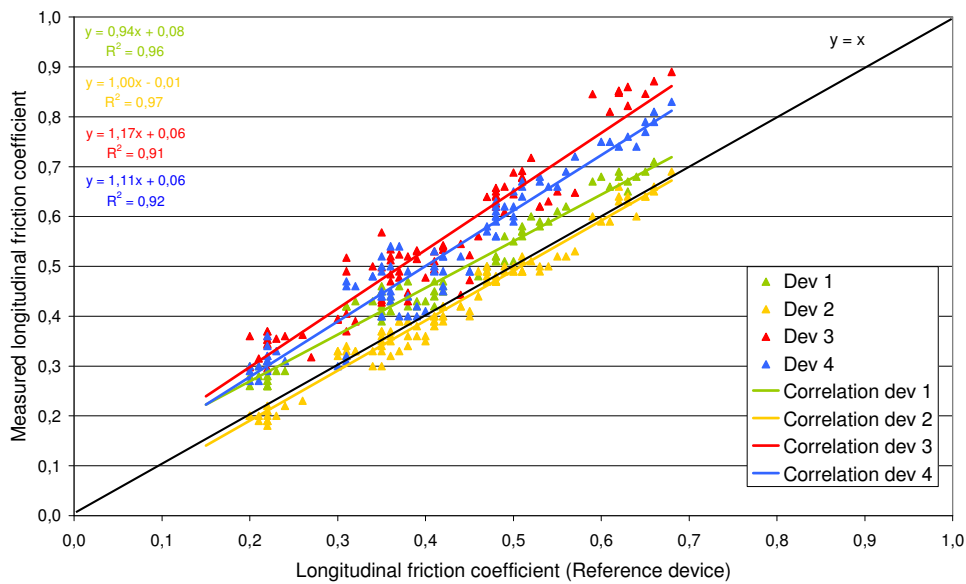


Figure 9 – Friction results for 4 different devices

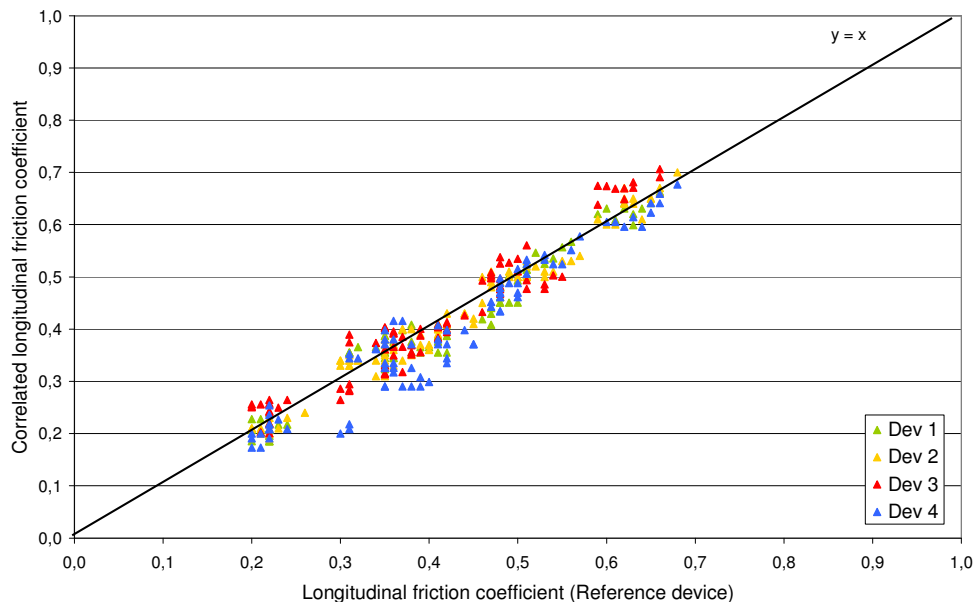


Figure 10 – Friction results after correlation

4.2. Stability of harmonization constants

A main proof of the quality of the methodology described in this paper comes from the reproducibility of the process. Reproducibility is assessed from the stability of harmonization constants. It is even more essential than initial correlation as it validates every measurements performed between two certification campaigns.

Previous international correlation trials have demonstrated that correlation constants may be very different from one campaign to another. The “device per device” approach used in this certification process allows comparing the very same device instead of a device among a given type of device.

Figure 11 presents test results and the regression obtained for the same device in June 2010 and August 2011. For both campaigns, the quality of the correlation is good. Figure

11 also shows that regressions are very close for both campaigns over the whole range of measured friction coefficients.

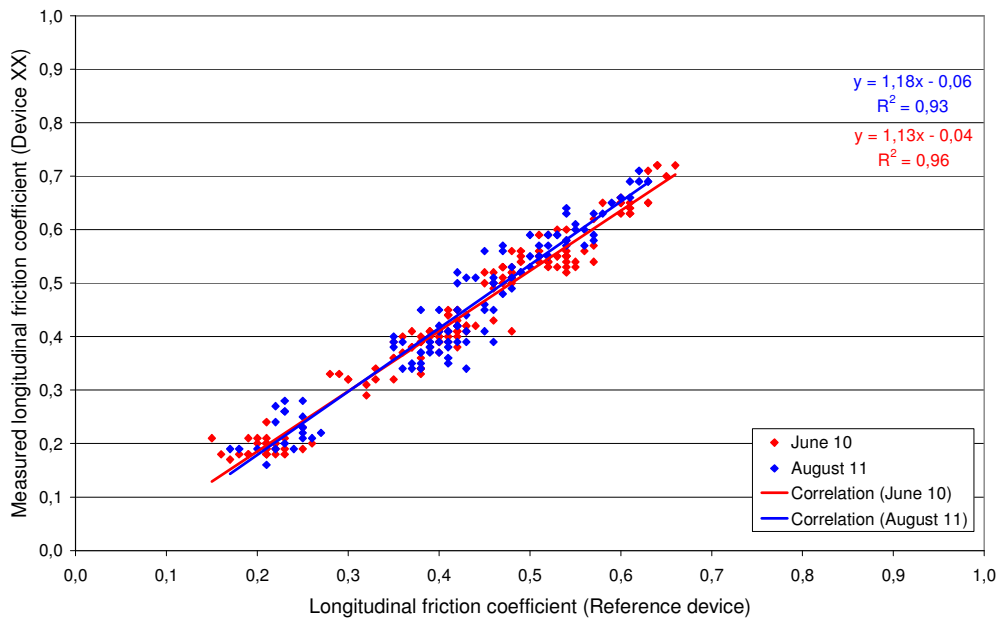


Figure 11 – Friction results for device XX in June 2010 and August 2011, and correlations

In figure 12 are plotted correlations and confidence intervals of the model for the same device as figure 11. As confidence intervals overlap, it can be inferred that both regressions are similar over this friction coefficients range.

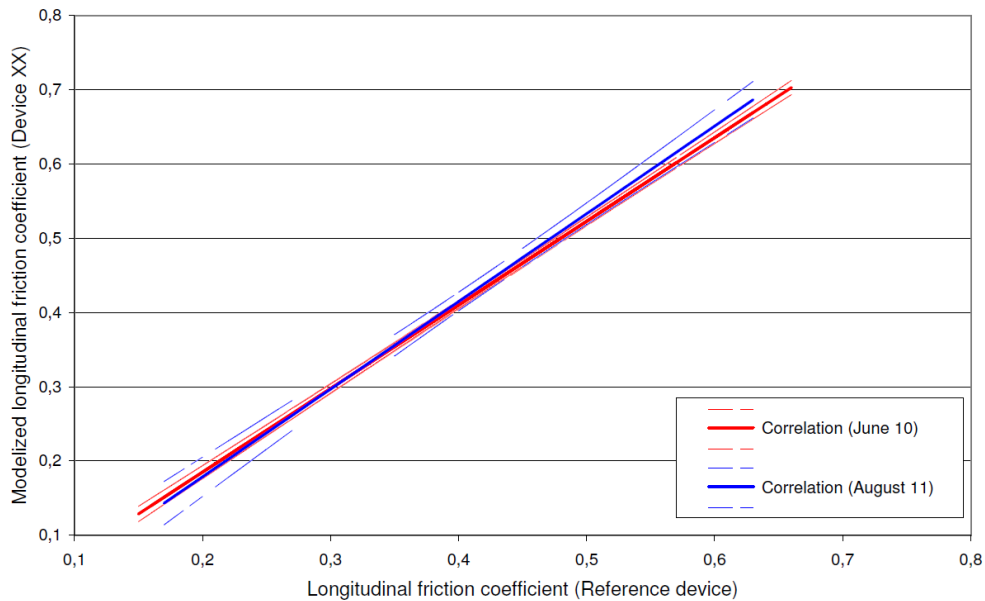


Figure 12 – Correlation and model confidence intervals

After six years of certification, 7 devices have been certified two times. Stability of correlation has been observed for 3 out of these 7 devices. This is satisfactory considering that, currently, STAC neither controls nor calibrates devices between two certification campaigns. Ways to improve reproducibility of correlation are presented in part 4.4.

4.3. Stability of the reference device

As a reference device, the IRV must be very stable in time. It is probably the most important issue concerning the correlation process.

Stability is ensured through an accurate calibration process performed before and after each campaign. The maximal accuracy error (E_j) allowed for the calibration process is $\pm 0,04$ friction unit. Figure 13 presents an example of IRV calibration.

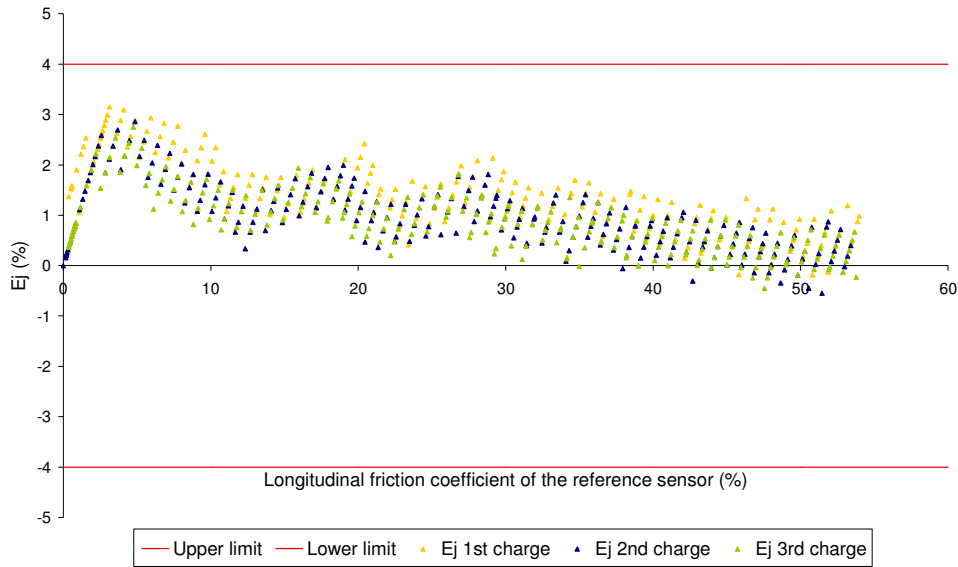


Figure 13 – Example of accuracy errors during calibration

Stability of the reference device has also been assessed by studying its results on the test surfaces. Figure 14 shows friction coefficients measured on surface E1 at 95 km/h over 6 years. The friction coefficient clearly tends to decrease due to aggregates polishing. Variations around this trend may be explained by meteorological conditions and variations in test parameters.

Assuming that the trend is the “real” friction coefficient, figure 14 demonstrates that measured friction coefficients remain between the lower and upper limits of the measurement uncertainty (as defined part 4.4).

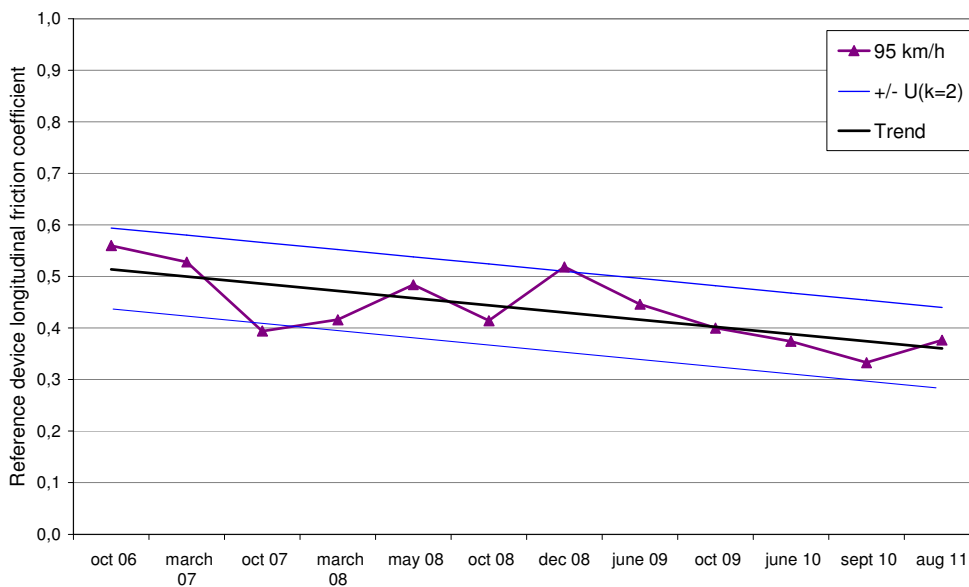


Figure 14 – Friction coefficient measured on surface E1 at 95 km/h with the reference device over a period of 6 years

Finally, part 4.2 demonstrated that correlation remains stable between devices from one campaign to the next one. This conclusion is a major proof of the reference device stability, as all these devices would not drift in the same way.

4.4. Uncertainty study

A precise knowledge of the reference device is of primary importance to ensure stability of this device.

Friction measuring devices are complex measuring systems and sources of uncertainties are various. Expanded uncertainty ($k=2$) for friction measuring device is therefore quite high. It explains why two devices may have significantly different behaviors when used on the same surface and why it is so hard to get stable harmonization constants.

The tolerance levels set by the STAC for correlation tests help reducing the measurement uncertainty and improve stability of harmonization constants. More and lower tolerance levels are needed to get better results.

The STAC is carrying out a study based on the Guide for the expression of uncertainty [8] to identify causes of variations of friction measurements and to quantify the influence of these causes, aiming to reduce them.

About 25 causes of errors have been listed, related to the measuring device, the test operator, the materials, the test method or the environment. These components of the measurement uncertainty have been classified according to the Ishikawa method [9] and are listed in figure 15.

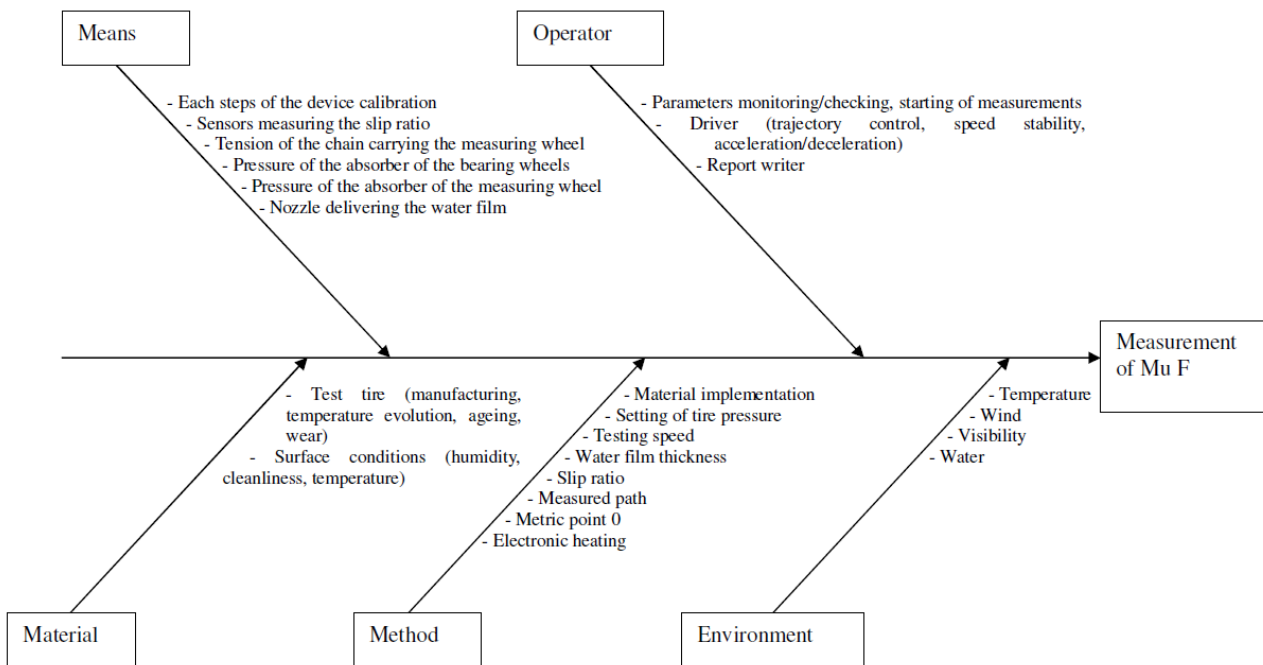


Figure 15 - Ishikawa diagram for the measurement of friction coefficient using the reference device

The following parameters have already been experimentally studied: tire wear, tire pressure, water thickness and nozzle height. These parameters have been studied around their nominal value. Table 5 presents each tested parameters. In particular, comparison tests have been performed between two tires manufactured the same year. One has been

stored according to requirements of AIPCR standards and run over 4 km before tests. The wear indicator is about 8 mm deep. The other one has been used regularly to perform tests until it reached the maximum wear allowed (wear indicator about 4 mm deep).

Table 5 – Test parameters

Parameters	High value (+1)	Nominal value	Low value (-1)
Tire wear	New tire	-	Used tire
Tire pressure	1,6 bar	1,5 bar	1,4 bar
Water flow	1,1 mm	1,0 mm	0,9 mm
Nozzle height	85 mm	75 mm	65 mm

An analysis of variance is performed to determine significant effects. An effect is considered as significant when the standardized effect, defined as the difference between means (mean value in test configuration 1 and mean value in test configuration 2) divided by the common standard deviation, is greater than 2.

$$\delta = \frac{\mu_2 - \mu_1}{\sigma}$$

An insignificant effect is removed from the analysis. Results, presented table 6, show that tire pressure and nozzle height have no significant effect on measurements, meaning that the tested values provide acceptable tolerances for these parameters. Results also show that strong interactions exist between parameters “tire wear” and “water thickness”, as illustrated in figure 16.

Figure 16 presents some results obtained for the new tire (+1) and the used tire (-1) at 0,9 mm water (-1) and 1,1 mm (+1). This figure shows that the difference between the new and the used tire reached about 0,10 friction unit. It also shows that interactions exist between parameters “tire wear” and “water thickness”. Indeed, when tests are performed with a used tire, the friction value is very dependent on the water flow, whereas the dependency is greatly reduced when tests are performed with a new tire.

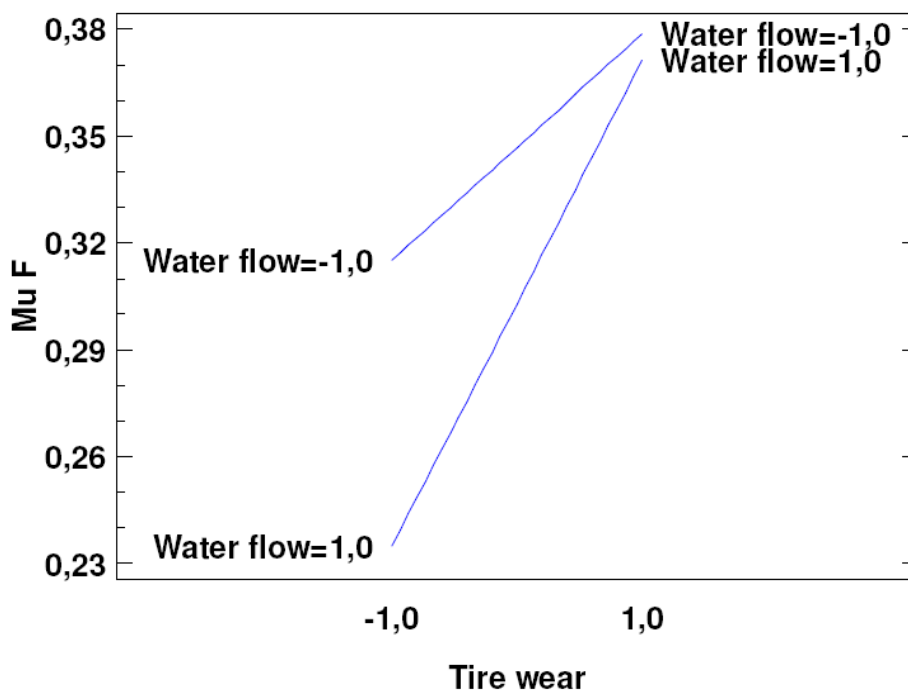


Figure 16 – Effect of tire wear, and interaction between parameters “tire wear” (+1 means new tire, -1 means used tire) and “water thickness” (+1 means 1,1 mm and -1 means 0,9 mm) on the friction coefficient (Mu F) at 95 km/h

Water thickness has a significant effect on friction coefficient when tests are performed at 95 km/h. It does not have significant effect at lower speed. Nevertheless, it is not possible to set up lower tolerance on this parameter due to uncertainties of the water flow sensors and capacity of the water flow servo-control. Moreover, some devices do not monitor water flow, so setting up tolerances on this parameter would be an issue. Tire wear has the most significant effect on the friction coefficient. To reduce possible errors due to this parameter on friction coefficients, all devices must be equipped with new tire during the certification campaign.

Table 6 – Estimation of effects on the friction coefficient (friction unit)

Coefficient	95 km/h		65 km/h		40 km/h	
	+ 1	- 1	+ 1	- 1	+ 1	- 1
Parameter value						
Tire wear	$5,00.10^{-2}$	$- 5,00.10^{-2}$	$3,66.10^{-2}$	$- 3,66.10^{-2}$	$2,00.10^{-2}$	$- 2,00.10^{-2}$
Water thickness	$-2,19.10^{-2}$	$2,19.10^{-2}$	$-8,48.10^{-2}$	$8,48.10^{-2}$	-	-
Tire wear X Water thickness	$1,83.10^{-2}$	$- 1,83.10^{-2}$	-	-	-	-
Tire pressure	-	-	-	-	-	-
Nozzle height	-	-	-	-	-	-

Further tests are planned to study influence of the following parameters: test speed, slip ratio of the measuring wheel and horizontality of horizontal force sensors.

Tests performed by the STAC showed that these tolerances allowed reducing measurement uncertainty at following levels:

Table 7- Expanded uncertainties (k=2) for the STAC's device

Test speeds	U(k=2)
95 km/h	0,08
65 km/h	0,06
40 km/h	0,05

By knowing precisely how the reference device behaves, the STAC will be able to reduce uncertainty on measured friction coefficients of the reference device. The quality and stability of correlations will be improved by setting tolerances for test parameters.

5. CONCLUSION

The certification process developed in France for friction measuring device allows correlating every self-wetting CFME to a reference device. It has proved to significantly improve reproducibility of friction measurements, especially when devices of different types are used. It is capital to ensure a uniform comprehension of friction measurements, especially for regulatory minimum friction levels.

Moreover, a “device per device” approach and specific test tolerances are solutions to the issue of correlation constants drift. Analysis of several correlation trials demonstrates that the constants are quite similar from one campaign to another. It is important to validate every measurements performed by the certified device between two certification campaigns. Unfortunately, it has not been possible to determine correlation constants per type of device yet. For some reasons still being investigated, two devices of the same type may have significantly different behaviors when used on the same surface. This

observation enforces the need to adopt a “device per device” approach concerning correlation and certification.

Last but not least, several years of measurements on the same test facility enable the STAC to claim that the reference device does not drift.

These conclusions legitimate the French practice concerning certification of CFME. Further works are needed to achieve better results concerning reproducibility of friction measurements and improve the quality of correlation. The STAC is carrying out an uncertainty study based on the Guide for the expression of uncertainty [8]. This study aims to identify causes of friction measurements variations, quantify influence of these causes and reduce them.

Improvement of devices may also be needed. Indeed, every type of friction measuring device is not able to record water flow, for instance, and thus cannot ensure the water thickness remains within specified tolerances.

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