Uncertainty Limits for an Aircraft-Based Runway Friction Assessment Method

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***Abstract* — A category combining runway excursion, abnormal runway contact, and runway undershoot/overshoot was the third leading cause of fatal commercial aviation accidents worldwide between 2005 and 2014, according to a study by Boeing [1]. A lack of timely and accurate information, regarding runway conditions, has been identified as a significant contributing factor. Since aircraft braking capability is not directly recorded in the current setting, a novel approach of using airplane data to identify real-time runway conditions is currently being evaluated. The airplane-based assessment relies on estimating the deceleration forces acting on the aircraft during the landing roll-out to deduce the runway friction coefficient. The accuracy of the airplane-based runway condition reporting is consequently dictated by the uncertainty associated with the calculation of the deceleration forces. This paper presents a methodology for defining acceptable uncertainty limits for the calculated forces based on the granularity of the friction reporting system, force estimation bias, and desired confidence level for the friction estimation. The methodology will then be demonstrated by evaluating the ability of a landing performance model for the Global 5000 aircraft to meet the prescribed uncertainty limits.**

***Keywords*- runway friction, aircraft braking action, uncertainty limits**

I. Introduction

A category combining runway excursion, abnormal runway contact, and runway undershoot/overshoot was the third leading cause of fatalities worldwide in the commercial jet fleet between 2005 and 2014, according to a study by Boeing [1]. The reduced friction on a runway due to runway contamination was a main contributor. A study by the Flight Safety Foundation determined that runway contamination is the third leading cause of runway excursion events [2]. Commercial aircraft continue to struggle with runway contamination due to a lack of timely, objective, and accurate information on runway conditions.

Currently, the primary methods of evaluating runway conditions are pilot braking action reports and continuous friction measuring equipment (CFME). Pilot braking action reports are a subjective method of characterizing the runway condition. This method of runway condition reporting provides up-to-date information on braking action, but the subjective nature of the method results in widely varying results between pilots and aircraft types. CFME is used to establish the friction characteristics of a runway and identify those areas of a runway surface that may require attention. Although it is a possible source of an objective measure of runway condition, CFME has limitations. The friction measurement obtained by the device does not directly map to the friction experienced by an aircraft tire. There is currently no objective type of measurement of runway surface condition that has been shown to consistently correlate with airplane performance in a usable manner to the satisfaction of the industry [3]. Furthermore, studies have shown that CFME often cannot provide repeatable results and the use of a CFME requires the temporary closure of a runway [3].

In the wake of runway excursion accidents in recent years, there has been a desire to improve runway conditions reporting and address the shortcomings of current braking action reporting methods. One possible solution is to use onboard aircraft data to estimate the runway friction coefficient. The aircraft braking capability cannot be directly obtained from onboard data; however, by analyzing each of the forces acting on the aircraft during the landing roll-out, the braking force can be deduced.

During the landing roll, the primary forces affecting the deceleration rate of the aircraft are drag, thrust, braking, and gravity (due to runway slope). Drag and thrust can be estimated using an aircraft performance model and recorded flight parameters (e.g., airspeed, N1, longitudinal acceleration, ground speed). The effect of gravity on the longitudinal acceleration of the aircraft can be estimated based on the slope of the runway. Data of braking torque or effective braking pressure are usually unavailable to support the calculation of braking force; however, braking force can be determined by balancing the forces acting on the aircraft given that flight data and adequate models are available to calculate thrust, drag, runway slope effects, etc.

Successful implementation of this procedure would provide an objective and repeatable measurement of runway friction that could be communicated in real time; nonetheless, this method presents its own set of challenges. One of the primary concerns is the uncertainty associated with the calculation of the forces acting on the aircraft. Without an accurate

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calculation of the drag, thrust, and gravity forces, the method may consistently produce erroneous results.

To address the friction calculation uncertainty issue, two sets of research questions need to be addressed. The first is: how can the uncertainty in the calculation be quantified? To answer this question, the uncertainty in both the inputs into the model and the model itself must be explored. The second research question is: what level of uncertainty for the method is acceptable? This is the question which this paper explores.

The analysis begins with a conceptual overview of the factors that will drive the uncertainty limits — namely, the granularity required for runway condition reporting will be reviewed. Subsequently, a mathematical formulation will be derived in Section III that represents the concepts explored in Section II. The application of the derived uncertainty limits will be demonstrated in Section IV using a landing performance model and flight data for a Bombardier Global 5000.

II. Runway Condition Reporting Granularity

A primary factor considered in developing uncertainty limits is the level of granularity used in runway condition reporting. As the coarseness of the granularity of the reporting system increases, the uncertainty limit constraints can be relaxed. In general, the runway friction coefficient is rarely directly reported; rather, the braking capability is characterized using runway condition codes or pilot braking action report (PIREP) terms: nil, poor, medium to poor, medium, good to medium, good, or dry. Creating "bins" of mu values that map to a runway condition description will define the granularity of the runway condition reporting system, which will have a direct impact on the friction calculation uncertainty limits.

Following the Southwest Airlines accident at Chicago's Midway International Airport in December 2005, the FAA chartered a Takeoff and Landing Performance Assessment Aviation Rulemaking Committee (TALPA ARC) to review the safety issues involved in operations on contaminated runways. One of the findings of the committee was a lack of standardized runway condition reporting. In response to this problem, the TALPA ARC released the Runway Condition Assessment Matrix (RCAM) tool in 2009, with the goal of creating a less subjective runway condition reporting system. Since 2009, the matrix shown in Figure 1 has undergone multiple iterations and validation studies [4]. The matrix consists of seven codes that are used to describe the runway condition. Airport operators are asked to divide the runway into thirds and assign a code to each section, creating a three-digit code for the runway as a whole. The codes are assigned based on the runway description, mu value, deceleration and directional control observation, and corresponding PIREP found in the table.

The mu values listed in the third column of the RCAM create bins of mu values that link a friction measurement to a runway condition code. The version of the RCAM shown in Figure 1 has overlapping bins due to uncertainty regarding mapping measured runway friction coefficients to runway condition codes. It is worth noting that the approximate ranges defined in the RCAM serve as guidance for mapping a mu value produced by a generic friction measuring device to a runway condition code and they are intended to only be used to downgrade a runway condition code. Airport operators should use their best judgment when using friction measuring devices for downgrade assessments, including their experience with the specific measuring devices used [4].

Airport Runway Condition Assessment				Pilot Reports (PIREPs) Provided To ATC And Flight Dispatch
Assessment Criteria		Downgrade Assessment Criteria		
Code	Runway Condition Description	Mu (μ) [1]	Deceleration And Directional Control Observation	PIREP
6	• Dry		-	Dry
5	*1/8" or less depth of:* • Wet (Damp or Water 1/8" or less) • Water (Includes Wet or Damp) • Slush • Dry Snow • Wet Snow	40 or Higher	Braking deceleration is normal for the wheel braking effort applied. Directional control is normal.	Good
4	• Frost *-15ºC and Colder outside air temperature:* • Compacted Snow	39	Brake deceleration and controllability is between Good and Medium.	Good to Medium
3	• Wet ("Slippery when wet" runway) • Dry Snow or Wet Snow (Any Depth) over Compacted Snow *Greater than 1/8" depth of:* • Dry Snow • Wet Snow *Warmer than -15ºC outside air temperature:* • Compacted Snow	to 30	Braking deceleration is noticeably reduced for the wheel braking effort applied. Directional control may be noticeably reduced.	Medium
2	*Greater than 1/8" depth of:* • Water • Slush	29 to	Brake deceleration and controllability is between Medium and Poor. Potential for hydroplaning exists.	Medium to Poor
1	• Ice [2]	21	Braking deceleration is significantly reduced for the wheel braking effort applied. Directional control may be significantly reduced.	Poor
0	• Wet Ice [2] • Water on top of Compacted Snow [2] • Dry Snow or Wet Snow over Ice [2]	20 or Lower	Braking deceleration is minimal to non-existent for the wheel braking effort applied. Directional control may be uncertain.	Nil

Figure 1. TALPA Runway Condition Assessment Matrix (RCAM)

TABLE I. Conceptual Braking Action Scale

Estimated Braking Action	Measured Coefficient
Good	≥f5
Medium to good	[f4, f5)
Medium	[f3, f4)
Medium to poor	[f2, f3)
Poor	[f1, f2)
Nil	< f1

Ultimately, a single coding system would be desirable to classify the runway conditions, with clearly defined bins given that a systematic method to estimate or measure the runway surface condition is available. For demonstration purposes, Table 1 provides a conceptual mapping of measured coefficients to estimated braking action. The f1, f2, f3, f4, and f5 notations are placeholders for mu values and must be defined such that f1 < f2 < f3 < f4 < f5. The range of friction coefficients for each bin defines the granularity of the reporting system. Using the notion described, uncertainty limits will be derived that can be applied to a defined braking action scale.

III. Uncertainty Limit Derivation

The conceptual braking action scale defined in the previous section demonstrates a mapping of measured friction coefficients to reported braking action. Along with the braking action scale, a desired confidence level (i.e., the acceptable probability of the algorithm producing the correct braking action report) must be defined to prescribe uncertainty limits. If the confidence level is set low, then the number of occurrences of an over- or underestimation of the runway friction code will be high. An overestimation of the code creates a false confidence in the available friction coefficient of the runway and may cause a runway overrun. An underestimation of a code could cause premature or unnecessary closure of a runway in adverse weather conditions, which would be costly to airlines and airport operators. This section will explore possible bounds for the confidence level of the aircraft-based friction assessment method and provide a mathematical formulation for defining bounds on the mean and standard deviation of the force calculation uncertainty. First, the estimation error for the friction coefficient will be defined. This will provide a mathematical formula that will determine the expected error for the friction calculation. Using the error formula and the braking action scale, the friction uncertainty limits will be defined. Then, to provide a more intuitive understanding of the uncertainty, the friction limits will be transferred into uncertainty limits for the force calculation.

A. Friction Coefficient Estimation Error Definition

To begin the analysis, a definition of the expected error in the calculated friction/mu (f_{calc}) is needed. The calculated mu value is dependent on the calculated deceleration forces other than braking on the aircraft (F_{calc}), estimated aircraft mass (m), and calculated lift (L).

$$f_{calc} = \frac{ma - F_{calc}}{mg - L} \quad (1)$$

The calculated mu will likely not be a perfect representation of the actual mu since the estimated forces are a combination of the true force value and errors caused by inaccuracies in measurement devices and the model. (The parameters are summarized in Table 2.) The error in the calculated forces will translate to an error in the friction estimate. Subsequently, the calculated mu is the sum of the actual mu (f_a) and the mu error (f_e).

$$f_{calc} = f_a + f_e = \frac{(F_{xa}+F_{xe})-(F_a+F_e)}{(W_a+W_e)-(L_a+L_e)} \quad (2)$$

TABLE II. Friction Calculation Parameter Names

Symbol	Parameter Name
F_{xa}	Measured longitudinal force
F_{xe}	Longitudinal force measurement error
F_a	Actual deceleration forces (excluding braking)
F_e	Calculated deceleration forces error
W_a	Actual aircraft weight
W_e	Aircraft weight estimation error
L_a	Actual lift
L_e	Lift estimation error
N_a	Actual normal force on main gear

The true mu value is a function of the actual forces acting on the aircraft, as shown in (3). Then, by substituting (3) into (2) and solving for mu error, (4) can be derived.

$$f_a = \frac{F_{xa}-F_a}{W_a-L_a} \quad (3)$$

$$f_e = \frac{(F_{xe}-F_e)(W_a-L_a)-(F_{xa}-F_e)(W_e-L_e)}{(W_a-L_a)[(W_a-L_a)+(W_e-L_e)]} \quad (4)$$

While all force calculations will have errors associated with them, the effect of errors on drag and thrust far outweigh the effect of errors on weight, lift, and measured inertial data on the total mu error. Therefore, for simplicity, it is assumed: $W_e \to 0; L_e \to 0; F_{xe} \to 0$. Then, the mu error equation can be reduced to:

$$f_e = -\frac{F_e}{W_a-L_a} = -\frac{F_e}{N_a} \quad (5)$$

Equation (5) represents the mu error if the force error is deterministic. However, in reality, the force errors are random variables. Given that the errors are normally distributed and setting f_e equal to the random variable X and setting F_e equal to the random variable Y:

$$X = N(\mu_X, \sigma_X) \quad (6)$$

$$Y = N(\mu_Y, \sigma_Y) \quad (7)$$

Applying the change of scale operation for normal distributions, the expected value (E(X)) and variance ($\sigma^2(X)$) of the mu error is:

$$E(X) = -\frac{\mu_Y}{N_a} \tag{8}$$

$$\sigma^2(X) = \frac{\sigma_Y^2}{N_a^2} \tag{9}$$

Now that the expected value and variance of the mu error has been defined, the next step is to define a confidence level for the calculation. The expected value and variance constraints can then be calculated using the desired confidence level.

B. *Friction Calculation Confidence Levels and Error Distribution Constraints*

The uncertainty limits for the friction calculation will be directly tied to the categories defined in the braking action scale. The friction values are shown in graphical form in Figure 2. The values of f1–f5 are boundaries that define a range of mu values for each runway condition category. Depending on how the values are assigned, each bin may not have an equal range of friction values. In order to prescribe the uncertainty limits, the smallest bin size must be identified. For demonstration purposes, a minimum bin size (Δf) of 4 mu will be used in the following example. (Note: 4 mu translates to a 0.04 friction coefficient.)

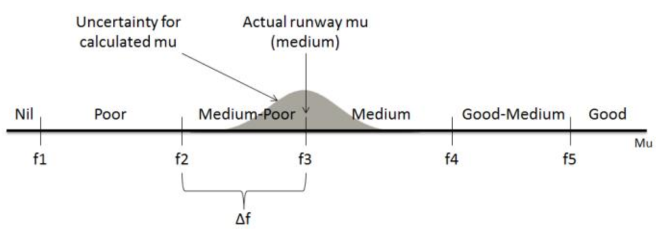

Figure 2. Braking Action Scale (*with uncertainty distribution*)

To implement the aircraft-based friction assessment method, stakeholders must determine the acceptable level of uncertainty produced by the algorithm. In this paper, it is considered that the calculated mu should not deviate more than ±1 category from the actual mu. (Note that the methodology presented could be carried out for other constraints.) The example illustrated in Figure 2 shows an actual runway mu of f3 and a range of Δf for the medium-poor category condition. For this analysis, let f3 be 30 mu and Δf be 4 mu. Assuming that the actual runway mu is 30 and the true runway condition is "medium," if the calculated mu is 25 (which is more than 4 mu less than the actual value), the runway condition would be reported as "poor" rather than "medium" (2 categories from the actual). Based on this restriction, it is proposed that limits are set on the allowable standard deviation of the mu calculation uncertainty distribution.

In practice, it is important to quantify the confidence interval for the calculation. Assuming that the errors are normally distributed, 99.73% of the results will fall within ±3σ of the mean and 95% of the results will fall within ±2σ of the mean. Returning to the example where the actual runway mu is 30, if the errors are normally distributed and not biased (i.e., the expected value of the error is 0), the expected value of mu will be 30. If it is desired to have 99.73% fall within ±1 category of the actual value, then three standard deviations of the calculated mu distribution cannot be greater than 4 mu.

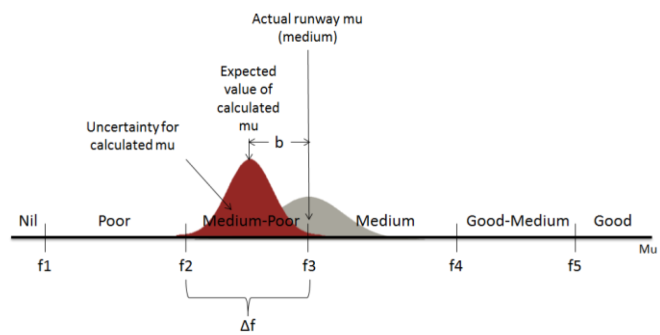

Figure 3. Braking Action Scale (*with biased uncertainty distribution*)

That is, the standard deviation of the mu error distribution ($\sigma^2(X)$) cannot exceed 4/3.

It is worth noting that the derived limit only holds if the model is not biased. In many cases, the model may consistently over- or underestimate the forces. Likely causes of a bias (b) are measurement bias or an incorrect coefficient in a model. If a bias is present, then the allowable standard deviation will decrease. For example, as shown in Figure 3, the allowable standard deviation will be decreased as the bias increases. For example, if the bias is 2 mu, the allowable standard deviation will become 2/3 if a 99.73% confidence level is required.

To meet the ±1 category requirement and the desired confidence level, the mu error bias could range from 0 (no bias) to 4 mu. A plot of the allowable standard deviation vs. mu bias for a 99.7% and 95% confidence level is shown in Figure 4.

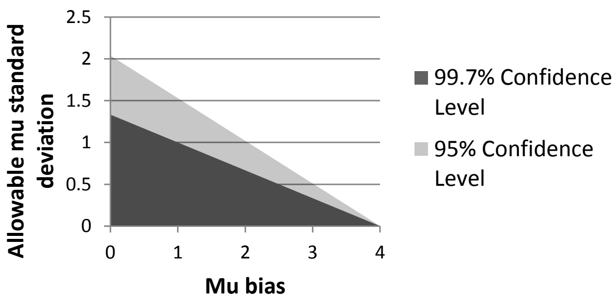

Figure 4. Allowable Standard Deviation for mu Uncertainty Distribution

The limitations on mu are useful in defining the uncertainty distribution for the calculated mu and understanding how that translates to the braking action categories. However, when evaluating a model being used for the friction calculation method, it is more intuitive to evaluate the error on the force calculations — meaning that limitations on the force error distribution should be set as well.

C. Force Calculation Uncertainty Limits

Based upon the confidence level selected, the limitations on the expected value and variation of the mu error can be translated to a limit on the force error bias and standard deviation using (8) and (9).

If the model is not biased, the variance limit for the force uncertainty is $\sigma_Y = \frac{4N_a}{3}$. Otherwise, if the model is biased, then:

$$E(X) = \frac{b}{100} = -\frac{\mu_Y}{N_a} \tag{10}$$

$$\sigma^2(X) = \left(\frac{4-b}{3}\right)^2 = \frac{\sigma_Y^2}{N_a^2} \tag{11}$$

Contour plots of (10) and (11) are shown in Figures 5 and 6 for a confidence level of 99.73%. The plots can be used to determine whether the distribution of errors for the force calculation fall within the prescribed uncertainty limits.

To use the plots, first the bias on the force calculation of the model must be determined. Then, using the expected normal force on the main gear, the calculated mu bias can be found using the plot in Figure 6. The mu bias is a single point only when evaluating a discrete normal force. However, the normal force will vary between landings and over the course of the landing roll. Therefore, a range of normal forces should be defined, which will result in a range for the calculated mu bias.

Once the calculated mu bias (either a discrete value or range) is known, the plot in Figure 5 is used. Based on the calculated mu bias and the expected normal force on the main gear, the limit for the allowable standard deviation on the force uncertainty can be determined.

IV. Example Model Analysis

To demonstrate the feasibility of meeting the uncertainty distribution constraints, a landing performance model for the Global 5000 was created using MATLAB/Simulink [5]. The model calculates the effects of thrust, drag, and runway slope on the aircraft during the landing roll using a variety of inputs from a quick access recorder (QAR) data file. (It is important to note that the model used was specifically developed for the Global 5000, but it is conceivable that comparable models could be developed for other jet aircraft.) Thrust is calculated using a control volume approach and drag is calculated by estimating the drag coefficient based on aircraft configuration. The runway slope is estimated using aircraft pitch and published runway information. A more detailed description of the model is available in [6].

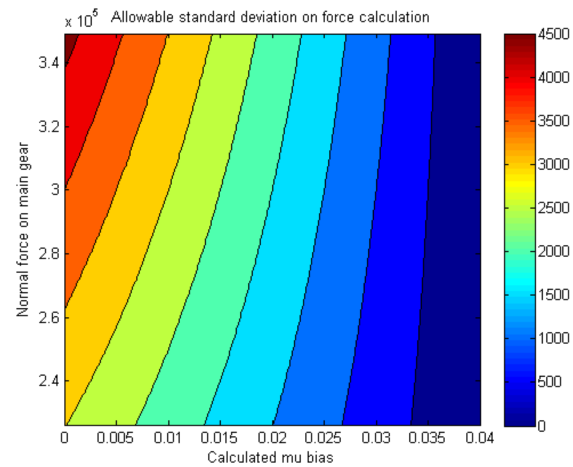

Figure 5. Allowable Standard Deviation for Force Calculation Contour Plot

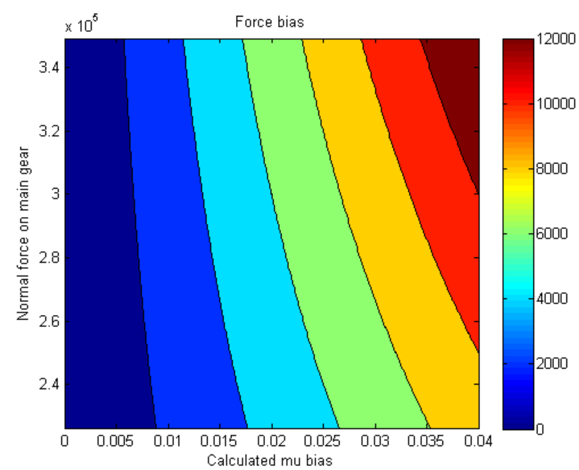

Figure 6. Calculated Force Bias Contour Plot

Campbell and Cheng [6] describe flight tests performed using the FAA's Global 5000 aircraft to validate their landing performance model. Those results are useful for evaluating the errors in the force calculation. When the flight tests were performed, the pilots were asked to delay braking until required for a safe stop. Using this technique, inertial data for the aircraft were collected that were not contaminated by the braking force (i.e., the only forces acting on the aircraft were thrust, drag, lift, and weight). If the model was perfect, there would be no difference between the calculated acceleration of the aircraft and the aircraft data; however, in reality, the model does contain errors and biases. The magnitude of those errors and biases are evaluated by evaluating the differences among the calculated forces from the recorded inertial data.

One issue encountered was that several parameters in the QAR data file were recorded at 1 Hz while the model calculates parameters at 4 Hz. During phases of the rollout when the forces were changing rapidly (e.g. thrust reversers are deployed), the discrepancy between the data and model frequencies caused relatively large errors. To mitigate this problem, Savitzky-Golay filtering [7] was used to smooth the QAR data. After applying filtering, a histogram of the errors was created using the JMP software, which is shown in Figure 7 [8]. The mean of the error is 356 N and the standard deviation is 3219 N.

Since the model contains a statistically significant bias, the allowable standard deviation needs to be calculated using the methodology presented in Section III. The first step is using (10) to transfer the force bias into a mu bias by varying the possible normal forces across the entire operational envelope. Based upon this input, the mu bias (*b*) could range from 0.10–0.16. Using the mu bias and (11), the range of allowable mu standard deviations (depending on the normal force) is about 1.13–1.14. Lastly, the allowable standard deviation for mu was translated to the allowable standard deviation for force, which ranged between 2561–3985 (depending on the normal force) using (11).

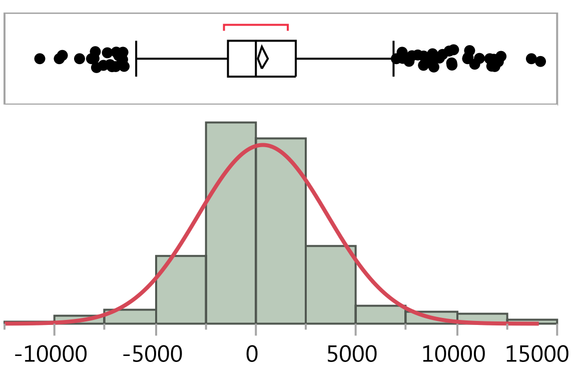

Figure 7. Model Error Distribution (N)

Our analysis showed that our model for the Global 5000 had an error standard deviation of 3219 N; therefore, the model would only meet the 99.7% confidence level when the normal force on the aircraft is greater than 283,259 N. If the required confidence level is relaxed to 95%, the minimum normal force for the model to be adequate is reduced to 232,111 N. The results show that in order to achieve a 99.7% confidence level, the model uncertainty must be reduced. To determine possible solutions for reducing model error, the primary sources of uncertainty must be identified. This process is demonstrated for the reverse thrust calculation in [6], where it was determined that the engine operating point and combustion temperature estimation were the primary sources of uncertainty for the reverse thrust estimation. If the uncertainties associated with those two parameters were improved, the range of normal forces for which the runway friction calculation would be valid would increase.

V. Conclusion

As stated in the introduction, this paper's purpose is to address the research question of: what level of uncertainty for the aircraft-based runway friction assessment method is acceptable? We developed a methodology to determine uncertainty limits for the calculation of runway friction. The limits prescribed depend on the granularity of the friction reporting system being used, bias associated with the calculation of the non-braking deceleration forces, and desired confidence level. For the presented methodology to be successful, friction coefficients must be mapped to a runway condition code or category. The range of friction values associated with each runway condition category will define the granularity of the runway friction reporting system. While the methodology was presented using the mu scale, it could also be applied to the Runway Condition Assessment Matrix or other braking action scales.

The mapping of the friction coefficient to the reported runway condition is just one input for defining the limits. A confidence interval for the calculation must also be selected. In the analysis presented, a 99.7% confidence level (3σ for a normal distribution) that the reported condition was within ±1 condition code of the actual runway condition was used. The confidence interval can be adjusted based on the user's needs. The analysis also showed that a bias in the forces calculation will further constrain the allowed variability in the friction estimation uncertainty distribution.

The methodology was demonstrated by evaluating a landing performance model that was developed for the Global 5000. By performing flight tests where braking was delayed, the model prediction of deceleration could be compared to the recorded deceleration of the aircraft. Using this technique, a histogram of the model error was produced. The analysis showed that our current model only met the uncertainty limits for a 99.7% confidence interval when the normal force on the main gear was greater than 283,259 N. Since the basic operating weight of the Global 5000 would produce a normal force of about 226,000 N, which is less than the required 283,259N, the model would not be sufficient in many situations. To mitigate this limitation, the required confidence level must be relaxed or the model uncertainty reduced. Ultimately, a balance between a realistic level of uncertainty for the force calculation and an acceptable level of uncertainty in runway condition reporting must be found.

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