FAA Aircraft Braking Performance Technical Working Group

Report and Recommendations

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Revision Summary

This report is a result of a 2019 effort to review and revise the original white paper presented in 2018. On June 6-7, 2019, the working group reconvened in Cambridge, MA to discuss changes in industry standards, practices, and safety initiatives, and to refocus the recommendations previously published. This paper has been extensively edited to present these issues in an updated manner.

Statement of Purpose

In 2016, the FAA's Research, Engineering, and Development Advisory Committee (REDAC) requested a formation of a working group to review ongoing and completed FAA research efforts on aircraft braking friction and to make recommendations regarding the direction of future efforts. Originally, efforts were focused on the 2007 NTSB recommendation A-07-64, ref (a). This recommendation has since been superseded as the *feasibility* of creating systems to record aircraft braking capabilities has been established. Follow on NTSB recommendations A-16-23/24 as noted in ref (b) and (c) state that the FAA should *"…work with operators and system manufactures to develop procedures that ensure that airplane-based braking ability results can be readily conveyed to, and easily interpreted by, arriving flight crews, airport operators, air traffic control personnel, and others with a safety need for this information*."

This follow-on recommendation, however, describes a very broad goal that must be supported by a system of safety components that can recognize hazards inherent to the gathering and integration of aircraft braking ability. These hazards involve how stakeholders in the National Airspace System (NAS) understand, process, manage and communicate aircraft braking performance. It is recognized by the working group that these components include:

1. Disparities in the current model used to predict the maximum friction that aircraft wheel brakes can achieve on a given runway as defined by the type and depth of the contaminant on the runway surface as published by the FAA in AC 25-32, ref (d). Studies, such as those listed in refs (e) and (f) have shown that for a given type and depth of contaminant, the maximum aircraft

wheel braking friction can vary significantly, and of concern is that it can be lower than that predicted by the current model. It may be possible to improve upon this current model by incorporating additional data from that currently used to further refine these predictions and reduce the risk of non-conservative landing assessments.

2. An apparent disparity in the FAA's model of wet runway wheel braking performance exists as defined in the equations listed in ref (g), FAR Part 25.109(c) and advisory circular 25-32, ref (d). The NTSB report in ref (h) makes a strong case that this model would benefit from a detailed analysis of both operational landing data on a large scale and a detailed study of wet runway braking properties in a testing environment. Factors to be considered include: runway micro- and macro-texture, runway design, pavement type, runway grooving, runway cross-slope, temperature, humidity, and rainfall rate. With a better understanding of these factors, it may be possible to predict under what conditions the expected wheel braking friction could be worse than predicted by today's model and thus give the airport and flight crew advanced warning of the possibility of experiencing significant degraded conditions.

3. For aircraft braking data to be effectively interpreted, it is necessary for proper procedures, policies, training, and operational risk management practices to be developed by an operator's SMS process. For this to occur, a report of aircraft braking must be universally understood as a standardized quantity whose properties and limitations are clearly understood.

Overview

The risk of a runway excursion or overrun increases when an aircraft unexpectedly experiences a significant reduction in expected braking performance after landing due to environmental runway contaminants such as rain, snow, or ice. This risk continues to result in accidents and incidents which can cause injury or death, incur significant operating costs, and reduce the faith of the flying public. A list of historic safety recommendations and accident analyses is found in Annex I.

An airport's ability to support operations with an effective safety margin during periods of active precipitation and contaminated runway conditions depends on the following aircraft-related capabilities:

1. The ability of an aircraft to observe and communicate when its braking limit has likely been reached.
2. The ability to describe and communicate that aircraft wheel braking limit using a scale that can be universally recognized.
3. The ability of all related stakeholders to recognize when the above process represents an agreed upon standard and what, if any, limitations that standard represents.

A significantly reduced braking condition can occur in an unplanned fashion due to the following potential hazards:

A. Changing runway conditions that occur too quickly for current observation and communication methods.
B. The inability to correlate aircraft wheel braking limits to observed conditions with enough precision to mitigate unacceptable uncertainty.

C. Modelling error in the methods used to predict wheel braking performance.

A specific standard relating to this issue is in the developmental process. Because this standard is intended to have an impact on a wide range of safety management processes to include applied research, participation and visibility to this ongoing activity is highly encouraged. The industry has taken the first steps with the American Society of Testing and Materials (ASTM) with the publication of standard **E3188-19:** ***Standard Terminology for Aircraft Braking Performance*** (ref i).

The engineering scale used to quantify aircraft braking performance is listed in **FAA AC 25-32** (ref d). This standard is in the process of being incorporated into ***ICAO Annex 6, Part II – Aeroplane Performance Manual*** (Doc 10064), expected to be published in final form in 2020.

Industry convention commonly refers to the system that produced the FAA guidance material as TALPA, referring to the Takeoff and Landing Performance Assessment (Advisory Rulemaking Committee "ARC"), ref (j). A summary of this process is described in Annex II. The ICAO term for this method is commonly referred to as the Global Reporting Format (GRF).

The hazards identified in this report can pose risks to both individual and organizational components of the National Airspace System (NAS). As such, the recommendations in this report are designed to address both a layered approach to safety as well as a more coupled approach to system performance. A brief discussion of a current method known as the *Volant* model of risk and resource management is included in Annex III.

Review of Ongoing and Previous Research

FAA research efforts have included testing with Boeing 727 and Bombardier Global 5000 aircraft. Broad Agency Announcement (BAA) agreements with Metron/Airbus and Aviation Safety Technologies (AST) as well as a Collaborative Research Development Agreement (CRDA) with Zodiac Aerospace were conducted. After a review of these programs, the working group has concluded the following:

1. The FAA Technical Center owns a non-airworthy B727 that has been specially instrumented for direct measurement of forces that relate to braking performance. The instrumentation and data collecting systems represent a unique configuration for a transport category aircraft to directly measure data unavailable in modern flight data acquisition systems.
    a. The aircraft has a Hydro-Aire Mark III analog anti-skid brake system with comparable efficiency to the newer digital systems (i.e. efficiency difference less than 5%).
    b. The B727 aircraft can perform braking runs up to 140 knots ground speed at the Atlantic City International Airport (ACY.) The aircraft is instrumented with strain gauges on the main landing gear axles allowing for direct measurement of wheel braking coefficients. The aircraft is also instrumented for direct measurement of wheel slip ratios and brake pressures both upstream and downstream of the anti-skid valves.

2. Testing with the B727 aircraft has been conducted under snow and wetted runway conditions for several years, generating mu-slip curves under varying runway conditions. These tests

provided insight into the ground friction characteristics of these surfaces and provided extremely valuable experience in sensing and data analysis. This experience included measuring friction limited wheel braking coefficients (μ_{brakes}) and associated wheel slip under varying snow and wetted runway conditions. Differential brake pressures across the anti-skid valves were used to validate friction limited braking.

3. The testing of the Global 5000 aircraft demonstrated that alternate sensing mechanisms are capable of recording flight data for aircraft wheel braking performance that can distinguish between different runway-related braking conditions. This potential capability could lead to effective tactical decision-making. The tests however were not able to be conducted with enough speeds and under the controlled conditions required to produce a proof-of-concept demonstration. Several aspects of experimental flight testing that would be required for a statement of function to reach FAA compliance proved challenging due to the way the project was managed. *It is recommended that future efforts include test crews and project management with more experience in STC planning and flight testing.*

4. The BAA contracts awarded to Metron/Airbus and AST demonstrated the feasibility of creating an *inferred* level of braking performance using the flight data that can be currently collected from the aircraft. At this time, these are the only two systems available and in use with the industry. While these methods were found to have value, there exists no independent standard where these methods can demonstrate their accuracy, precision, and compatibility between airplane models.

Additional Research

5. In 2016, the NTSB published a report titled *Slippery When Wet: The Case for More Conservative Wet Runway Braking Coefficient Models* (see ref h*.)* The report looked at six (6) accident investigations and documented a disparity between current wet runway braking models and runway descriptions and the post-accident braking analysis for each event. The overall conclusion was that current modelling of wet runway braking performance was not conservative enough to account for the conditions studied.

6. The FAA Aviation Research Division published a paper titled *Uncertainty Limits for an Aircraft-Based Runway Friction Assessment Method* (ref k). The paper explored the factors involved in using inferred data to calculate an aircraft wheel braking coefficient value that could be mapped to a generic scale such as TALPA and explored how a bias in such a method would affect the outcome. The result was that, for the aircraft in question, the Global 5000, a bias in calculating μ_{brakes} would effectively introduce too much variability in the results to be effectively used. This concept has been incorporated into the ongoing effort in ASTM to produce a standard for such systems that mitigates such potential system bias.

7. In 2012 and 2016, the Norwegian Technical Institute published two studies (refs e and f,) that detailed a comparison of *aircraft braking coefficients* (not to be confused with the TALPA standard of μ_{brakes}) with various observed contaminated winter runway conditions. These studies documented that, while specific descriptions of type and depth of contamination could be made, their precise relationship to aircraft wheel braking performance was at times non-

conservative with relation to the current guidance in AC 25-32 (ref d). This issue of RNWYCC to pilot reported braking was also the result of a 2013 study done by the Italian Civil Aviation Agency (see ref l) which documented the efficacy of the matrix between contamination and pilot braking reports. The result of this study revealed that there was a statistically significant occurrence where actual braking was less than what the TALPA guidance predicted.

8. Project #3 of Future Sky Safety – Europe initiative resulting from the European Action Plan for the Prevention of Runway Excursions. A summary report regarding braking on water contaminated surfaces along with other factors such as tire type and anti-skid systems is listed in ref (m). The Royal Netherlands Aerospace Center (NLR) published a paper in 2001 detailing their research on hydroplaning issues related to modern aircraft tires, ref (n), and is currently conducting research funded by the European commission looking at the effect of flooded runway as well as braking effectiveness contributions due to micro and macro texture on wet runway braking.

Aircraft Wheel Braking Measurement

Aircraft braking is defined per the terminology in ASTM standard E3188-19 in ref (i). There are two braking reports that can provide standardized information about an observed event, a pilot braking action report (PIREP) and an aircraft braking action report. The latter represents an objective engineering value, corresponding with FAA guidance material per AC 25-32 (ref d).

Due to the technical challenges involved with creating such an analysis, specialized and proprietary methods must be used. While an effort is underway to produce an international standard for these methods, none presently exist. While the results of the previously mentioned BAA have demonstrated that it is feasible for such reports to be produced, no method has yet passed a formal peer-reviewed acceptance criterion in the U.S. However, it is the consensus of this task group that sources of aircraft braking reports exist in the private sector that would be considered valid for research purposes.

While aircraft manufacturers may possess certification testing related flight data relevant to these discussions, proprietary concerns effectively shield any outside use. Commercial acquisition of aircraft wheel braking performance data from acceptable industry sources will most likely be necessary for large-scale data analysis that compares operational aircraft performance to other data collected external to the aircraft.

Gap Analysis

A. <u>Wet runway modelling</u>. The current model for wet runway wheel braking performance is taken from studies conducted by an FAA committee in the early 90's, European Aviation Safety Agency (EASA), and the Engineering Sciences Data Unit (ESDU) - an engineering advisory organization based in the United Kingdom. Today, there is a consensus that these current models may not represent operational conditions as they are presently observed as noted in the NTSB report in ref (h).

There is a need to identify the mechanism(s) behind the anomalies in the current model and how they can be identified. The previously mentioned research suggests that models of pavement micro-texture, water flow, and water level thickness play a significant part in defining where the observed braking performance departs from the established model.

The issue of transient rain poses a unique challenge for runway condition reporting as it is not currently possible to capture conditions that can change in such short time spans. Given some runway drainage characteristics, it is worth investigating if weather service radar and/or inflight radar returns can be correlated to water depth/drainage models on certain runways which can then be correlated to braking action. If so, it might then be possible to develop a method for tactically observing and communicating conditions that could indicate where standing water and/or degraded braking could be expected.

Further study and analysis of operational flight data needs to be accomplished to verify that the model anomalies are representative of a larger database. Current analysis in ref (h) shows there is a possibility that actual wet runway braking performance can be as low as 50% of the values provided by current models. There exists a potential for a better understanding of this phenomenon and the development of more predictive models of wet runway braking that could decrease the risk of runway excursions and overruns as documented by the NTSB.

Additionally, it is hypothesized that the current TALPA/GRF guidance may be based on a threshold of wetness (less than or equal to 3 mm water depth) that *exceeds the point where the current modelling becomes inaccurate*. The current model does not include the mean depth profile (MDP) of a surface's macrotexture and this may contribute to a bias in water depth reporting, an issue that may be a contributing factor to unexpectedly poor braking. A controlled study should be accomplished to observe if there is a specific means of measuring the level of water level thickness, given a set micro-texture and groundspeed, where the standard ESDU model is no longer accurate. If the relationship between macro-texture, micro-texture, runway drainage, and rainfall rate can be determined through a well-established and verified model, it would then be possible to correlate rainfall rate to the current failure point of the wet runway braking model and potentially predict a point where an operational runway becomes compromised.

B. <u>Validation and refinement of TALPA/GRF runway classification model</u>: The current correlation between type and depth of contamination has several issues affecting optimal employment.

   a. The relationship between current metrics for runway observation and aircraft performance produces a variability in the latter that negatively affects its use as a predictor of degraded braking (i.e. friction-limited braking). It may be possible that additional data sources such as humidity, temperature, dew point, etc., may be added to see if a correlation between reported runway condition and braking action can be further refined.

b. If a relationship between current metrics can be refined, then accuracy for both upgrading and downgrading of runway condition reports could result.

c. It has been observed that while most runways are compliant with FAA/ICAO practices for pavement maintenance, some runways appear to demonstrate substandard braking performance especially when wet. The identification of these runways and further analysis of their micro and macro-texture, drainage properties, and other possible factors should be accomplished in order to see if predictive cues are present.

C. Lack of industry standards for mapping braking performance to TALPA/GRF guidance. While the TALPA ARC and GRF guidance does provide a means for mapping aircraft wheel brake coefficient levels and associated models to braking performance, it did not provide a means for analyzing operational braking data in a manner that could be applied *back to* the matrix of braking levels. The Society for Aircraft Performance and Operations Engineers (SAPOE) in conjunction with ASTM is currently in the process of creating such methods and standards.

Currently, there is a challenge in taking friction limited wheel braking observations and using them as a predictor for TALPA/GRF style landing assessments at time of arrival. Whether the purpose of such an effort is to create effective operator policies for aircraft braking reports, or to investigate refinements in observations and analysis techniques, a robust partnership between academia and industry will be critical to an outcome that will reduce risk for the traveling public.

Recommendations

The following recommendations are centered around two basic problems. The first is that the specific model of braking performance on a wet runway appears to be in questions. The second is that the basic relationship between aircraft braking and observable factors external to the aircraft appears to require a more capable and accurate predictive model than current FAA guidance articulates in TALPA related guidance material.

Regarding activities proposed to address these issues, there are three data analysis methods discussed. The first is a big data approach to the analysis of aircraft braking reports by themselves to study the specific condition of wet runways. The second is a big data approach for the comparison of aircraft braking reports to all types of conditions and runway contamination. Finally, the recommendations describe a data collection plan that mirrors the specificity and detail of a flight certification program.

I. Analysis of aircraft recorded braking performance

Data collected from the aircraft, analyzed in such a manner as to create an accurate model of wheel braking performance that is mapped to the TALPA/GRF performance scale, must serve as the basic cornerstone for all analysis.

It is hypothesized that both clusters and branches of relationships exist between aircraft wheel braking data and exogenous features. Training a machine learning model to extract the relationships between contributing features and resultant degraded braking performance should extract these relationships. It will be necessary to ensure a sufficient variance and sample size of the data to ensure the applicability of the model in all trained conditions. If proven true, this would enable the current TALPA/GRF matrix to reduce unexpected exposure to risk through a refined mapping of contaminant to runway condition code as used in FICON's. A non-exhaustive list of hypothetical data sources to be included in modeling braking performance degradation is provided in Annex IV. Specifically, analysis of this type should be accomplished in support of the following applied research goals:

a. Improving the predictive qualities of the TALPA/GRF Matrix. The original means of providing a "reasonably conservative" predictive index for observable conditions in the TALPA ARC was explicitly intended to be improved upon. In this regard, it was always hypothesized that a more predictive means of correlating all observable conditions and braking performance could be achieved. This would include frozen contaminants as well any other quantifiable data that can reasonably be collected in an effective manner. A non-exhaustive list can be found in Annex IV. This effort should include, but not necessarily be limited to, a study using big data methods to develop statistical models that describe degraded wheel braking on various contaminations on a runway. The following research goals, b and c, are research goals for an ongoing research on degraded braking on wet runways; however, similar research goals will be established for other types of contaminations.

b. Identification of specific runways where wet braking is degraded below the current modeled threshold. It is hypothesized that specific runways can be identified where wet braking is observed to be consistently poorer than what the models in FAR 25 109(c) and (d) predict in ref (g). The degree of this degradation has been documented with specific examples in the NTSB report in ref (h). If it is possible to identify specific runways for which wet braking matches the NTSB scenarios previously described, then it would be possible to examine the characteristics of these runways to determine the causality of this effect and a new ESDU supported model could be fashioned for use in standardizing landing assessments under the conditions studied.

c. Identification of rain rates during transient weather conditions that can be tactically observed and communicated in a predictive manner *before* an aircraft touches down. It is hypothesized that current airport methods of observing and reporting wet runway conditions may not act as predictors for producing a water thickness that would result in braking performance less than currently predicted for “wet” runways. It is hypothesized that new opportunities for developing predictive modeling of wet runway performance may be achieved by correlating meteorological data outside the current TALPA guidance. Such data could include:

i. Specific runway water removal modelling, rain rate sensing, pavement characteristics, and runway characteristics (slope, crown, etc.)
ii. The correlation of certain modes and reflexivity levels of the National Weather Service S-Band WSR 88D radar system.
iii. The correlation of reflectivity levels from Air Traffic Control (ATC) primary surveillance radar (PSR) such as the ASR-9. As this radar is the primary vehicle for tactical observation of both ATC communications and weather avoidance vectoring.
iv. The correlation radar used onboard aircraft. Aircraft radar is typically of a different band than WSR radar, operates at a lower power out, and has a quicker scan.

II. International Standards Development

The working group members should support participation in the SAPOE/ASTM standards effort for the collection and reporting of friction limited aircraft braking information. Technical and philosophical challenges remain in MU-brake mapping to the TALPA/GRF reporting scale as well as other areas. As this process will ultimately define the outcome of all related research into aircraft landing safety, it is requested that the stakeholders associated with the technical working group as well as the overall REDAC process engage in this process if asked so that broader professional consensus can be formed with the final publication.

III. Controlled Condition Flight Testing

As mentioned in the gap analysis (A,) there is a need for detailed study of the phenomenon taking place whereby a wet runway starts to display properties that result in abnormally degraded aircraft wheel braking. Large scale data base analysis and big data studies using exogenic sources may result in the development of predictive statistical models that could be used to more accurately estimate expected degraded braking based on near real time information on runway conditions. However, the actual mechanism behind such a degraded braking anomaly is best determined by a detailed flight test program where variables of interest, including those which can only be obtained in controlled testing such as micro/macro texture, slope, water depth, can be accurately measured and controlled. The analysis of data collected from flight tests would be complimentary to the big data study in that it would help to validate predictive statistical models derived using big data study as well as to understand and explain contribution of particular factors, such as micro and macro texture, to the degraded braking.

It is hypothesized that a rational model can be created, capable of predicting the point where the tire to ground friction departs from the established FAA/ESDU model. Such a model would take into consideration new types of runway specific factors as well as weather observation methods.

This would require three elements: A test aircraft, a test facility, and a test plan. Each is detailed below.

a. It is hypothesized that a testing plan with an aircraft representative of a modern transport category type, would be able to identify the specific relationship between runway characteristics, groundspeed, and water depth/thickness whereby aircraft friction limited wheel braking departs from current wheel brake models and behaves in a manner observed in NTSB studies. This degraded model would have previously also been supported by large scale flight data analysis as outlined in recommendation I. If this hypothesis holds true, then a new model of braking assessment could be fashioned for use in a revised TALPA/GRF scale to minimize risk in the future.

In support of the above proposed experiment, the following supporting resources would be necessary. Obtaining a dedicated aircraft and the large-scale construction of a dedicated pavement area for test and evaluation has been considered by the working group and is considered cost prohibitive. However, utilizing a current runway of acceptable length and maintenance as well as leasing an aircraft from other government agencies or private sector can be used. KACY (Atlantic City) and KWAL (Wallops Flight Facility) are good examples of such runways as they are proximate to research centers. The following characteristics for an aircraft, test runway, and test design are desired.

<u>Test aircraft:</u>

- Similar in type to a B737NG or A320.
- A modern, fully modulating digital anti-skid system as referenced in AC 25-32 and AC 25-7C, ref's (d) and (o).
- Airworthy. The aircraft must fly to test sites where natural and controlled conditions can be experienced.
- The aircraft must be capable of landing speeds of up to and including 140 knots.
- The aircraft must be capable of being operated under an experimental certificate.
- The FAA must have at its disposal, a test pilot who is a graduate of a test pilot school recognized by the Society of Experimental Test Pilots and who holds a current FAA certificate of a Flight Test Designated Engineering Representative (DER).
- If possible, the aircraft should have the capability to accommodate additional sensors in support of aircraft wheel braking research.
- A source of flight data that can be readily accessible and robust for analysis by an entity with an acceptable method for producing aircraft wheel braking coefficient data as well as aircraft braking reports.

Testing Runway: A testing facility with an available runway should be obtained, meeting the following criteria:

- Minimum 8000’
- Allow full scale testing of transport category aircraft of a similar size and weight as a 737-700 or A-320.
- Contain a test area with the following criteria:
  - Allow for a testing run of a minimum of three seconds at 140 knots.
  - Be positioned for accelerate to stop and landing roll testing.
  - Have a capability of maintaining a specific level of standing water in incremental depths the test section.
  - Provide adequate safety areas both laterally and longitudinally to comply with flight test safety criteria as determined by the flight test DER.
  - Test runway geographically located to ensure that testing can be conducted during winter weather snow events.

Test Design:

A testing plan should be designed by a multi-disciplinary team including statisticians, aerospace engineers, civil engineers (familiar with pavement characteristics), and a flight test DER who is a graduate of a recognized test pilot school and is knowledgeable with modern safety test practices as published through the society of experimental test pilots. This testing plan should incorporate all best practices to be coordinated with the selected test facility and those responsible for the desired outcome of the experiment.

Annex I

Safety Recommendations and Accident Analysis

NTSB recommendation A-07-64 was superseded by NTSB A-16-23 and 24 as listed in refs (b) and (c).

NTSB A-16-023: Continue to work with industry to *develop the technology to outfit transport-category airplanes with equipment and procedures to routinely calculate, record, and convey the airplane braking ability* required and/or available to slow or stop the airplane during the landing roll.

NTSB A-16-024: If the systems described in Safety Recommendation A-16-23 are shown to be technically and operationally feasible, *work with operators and the system manufacturers to develop procedures that ensure that airplane-based braking ability results can be readily conveyed to, and easily interpreted* by, arriving flight crews, airport operators, air traffic control personnel, and others with a safety need for this information.

Additional NTSB visibility for this subject was articulated in a 2015 recommendation communicated as a comment to the FAA Advisory Circulars (AC's). The comment read;

> "The NTSB encourages the FAA to perform flight tests on representative domestic and international runways that support turbine-powered airplane operations in order to validate the wet-ungrooved and wet-grooved wheel braking coefficient models in Section 25.109(c). The NTSB believes that issuing these draft ACs relying on the untested and potentially insufficiently conservative models in Section 25.109(c) is premature. The suggested ARAC flight test validation work should be used to update the wheel braking coefficients appropriate for wet runway operations." *(Emphasis placed by the editor.)*

In 2017 an FAA Aviation Rulemaking Advisory Committee (ARAC) Flight Test Harmonization Working Group made the following recommendations:

> *"It is recommended airplane certification and operational performance organizations to work directly in a regulatory agency sponsored team with airport organizations on a method to quantitatively identify runway conditions leading to poor performing wheel braking on wet runways and using this information to identify poor performing wet runways."*

> *"The current standards are reliant on Continuous Friction Measuring Equipment (CFME) which are typically not available at the runways that have reduced wet wheel braking capability. Other techniques of recognizing poor wet runways need to be established that can be used at airports that do not have access to CFME equipment or that can be used in combination with CFME's. These techniques need to be specific and have meaning as to airplane stopping performance."*

Finally, in December of 2017, the Commercial Aviation Safety Team (CAST) issued Safety Enhancement 222R1 as detailed in ref (p.) The report states the following:

> *"… the team determined that qualitative reports of runway friction based on pilot perception could be augmented, improved, and ultimately replaced by quantitative calculations of runway friction derived by onboard measurement and data processing systems. The aviation industry should conduct research to enable development, implementation, and certification onboard aircraft system of technologies to assess airplane braking action and provide the data in real time to the pilot, other aircraft crews, air traffic controllers, and the airport operators."*

The actions recommended were;

> *1. FAA Aircraft Certification Service (AIR) will continue support for research currently underway on onboard aircraft system of technologies to assess airplane braking action and provide the data in real time to the pilot, other aircraft crews, air traffic controllers, and the airport operators.*

2. FAA AIR will track research results and report conclusions to (Joint Implantation Measurement Data Analysis Team) JMDAT and CAST."

Aircraft Braking and Accident Analysis

These recommendations at least to some degree were based on the investigation of the 2005 737 overrun at the Chicago Midway airport. The chart in Figure 1 was provided by Boeing as part of the NTSB public hearing. It shows the analysis of the wheel braking contribution to aircraft deceleration comparing previous 737 aircraft landing on the same runway immediately prior to the accident (red diamonds). The chart also shows the PIREPs (PIlot REPorts) of braking action reported to the tower.

The chart shows there was a measurable reduction in wheel braking available based on analysis of the parameters available on the aircraft in the FDR (Flight Data Recorder) data. If this information had been made available to the airport and/or the flight crew it is possible different decisions would have been made which could have resulted in an avoidance of the accident.

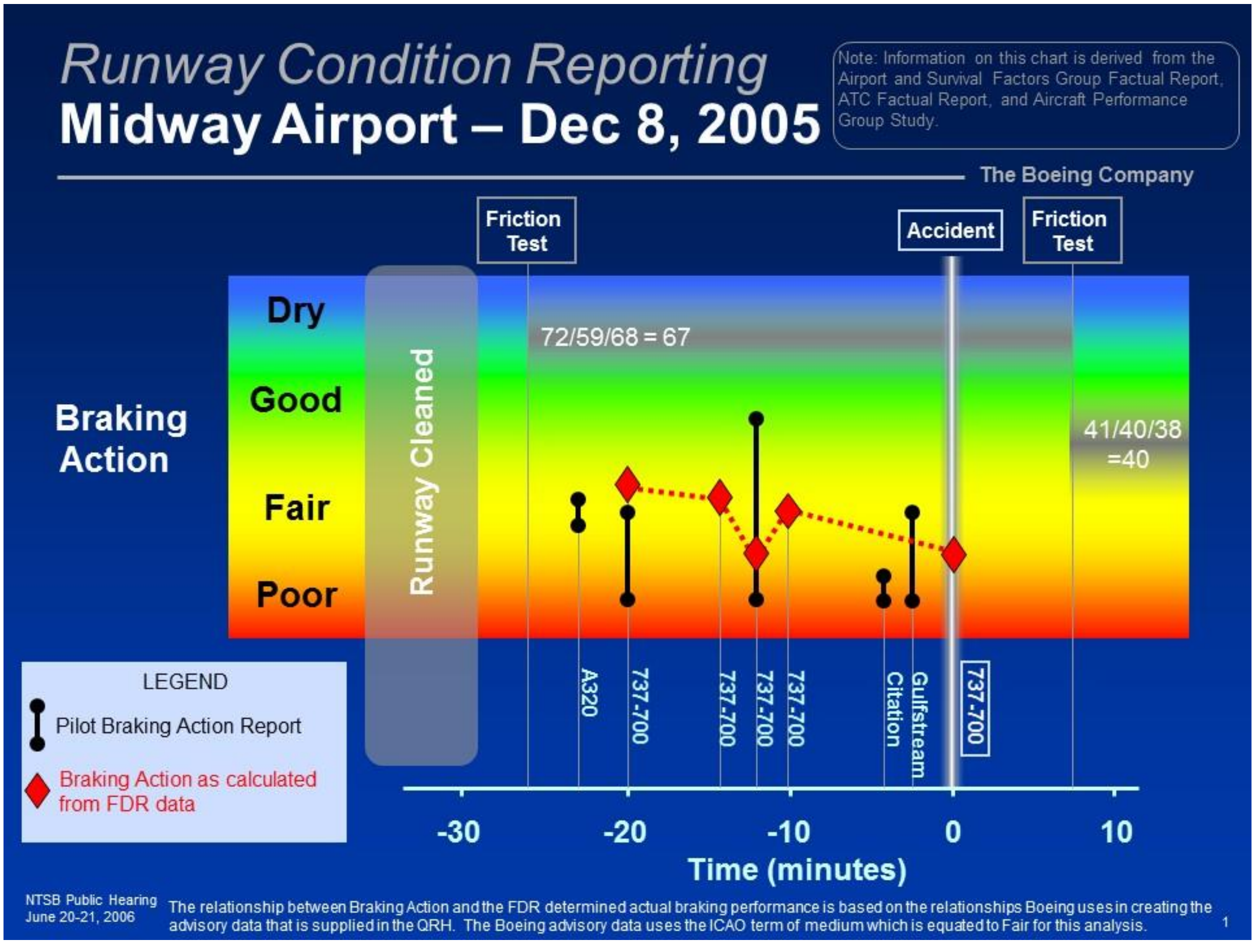


Figure 1. NTSB Public Hearing document

Figure 1 references various braking levels, today those terms and braking levels have been accepted by the FAA in AC 25-32 (ref (d.)) This AC and many others relating to aircraft braking and runway conditions were based on agreed methods determined by the FAA's Takeoff and Landing Performance Assessment Advisory Rulemaking Committee, otherwise known as the "TALPA ARC." To better facilitate an understanding of the issues, a brief background discussion on the TALPA ARC follows.

Annex II

TALPA ARC Overview

The overrun of a 737 in Chicago MDW airport in 2005 started a detailed examination of several issues that had been embedded in aviation for over 30 years. Among those were two major shortcomings: First, there was no industry standard for predicting aircraft landing performance for conditions that were more slippery than a normal wet surface. Second, there was no standardized method in which any predictions could be made for surfaces contaminated with snow, standing water, slush or ice. The TALPA ARC was formed to address these and other preconditions for unsafe acts in the form of recommended rulemaking. The official FAA description of the program can be found in ref. (j.) To place the analysis and recommendations of this group in context, the following description of the program is provided.

<u>A new method for managing safety</u>:

The solution at the time was not to be found with any new breakthrough technology. The methods available for creating a proposed solution were; airport observations, airport friction readings, previous industry studies, and pilot reports.

The TALPA ARC then was faced with a unique problem, every method that could be used had both strengths and weaknesses. It was decided that a layered approach to risk management should be developed by employing methods of observation currently in use and employing industry studies to form better methods of prediction. The basic approach was as follows:

1. For the ***first*** aircraft to land, a matrix was created that listed specific runway states (wet/dry) as well as contaminate type and depth descriptions. Along with outside air temperature, these descriptions were then used to create a reasonably conservative correlation to expected aircraft wheel braking performance.

2. The abilities of ground friction measurement devices were then added to potentially act as a check by indicating that braking could be worse than estimated by the first method.

3. Finally, the pilot observation of braking would serve as the last layer in the quality assurance process. The value of this perspective was considered to have the highest degree of reliability.

While each method had the potential to produce corrupt data, the process of using each type of observation as a progressive quality assurance check provided a significantly higher degree of conservative risk management than previous practices.

The relationship between aircraft engineering, runway descriptions, ground friction measurements, and pilot reports was called “the matrix” and is often referred to as the “RCAM” for Runway Condition Assessment Matrix.

Mimicking the practice of Threat and Error Management, a communications protocol was developed that attempted to prevent corrupt data from entering the system. By focusing specific information to specific types of operations, a potential barrier to errors in communication and understanding was created. The result was three different versions of RCAM.

- Operators (pilots, airlines) would use the guidance found in AC 91-79a (ref (q).) This purposely did not include ground friction measurements nor aircraft certification guidance.
- Airports would use AC 150-5200-30D (ref (r).) This ***would*** include ground measurement guidance for downgrades and in one specific case, an upgrade.
- Performance engineers would use AC 25-31 for takeoff and AC 25-32 (ref (d)) for landing which contained specific engineering guidance on creating takeoff and landing performance data. As these engineering values form the basis for establishing braking levels and therefore exposure to risk, we will also look at a brief background on this subject and the TALPA recommendations.

Measuring aircraft braking performance:

Measuring aircraft landing and braking performance had long been an industry practice used during certification and accident/incident investigation. The certification process for transport category aircraft has utilized a method involving a braking coefficient that describes how much of the downward weight an aircraft or a specific wheel could be transferred into a braking force. Test aircraft were specially instrumented to measure these forces during certification runs on dry runways. This data was then used along with parameters derived from flight testing (lift, drag, thrust etc.) of the individual aircraft in conjunction with previous industry studies to create “approved” data for various braking levels on non-dry surfaces. For example, British CAA certification required data for wet and ice-covered runways. In the 80s, it was acceptable to use ½ the dry runway braking coefficient for wet, etc.

While the distinction may seem minor, there was a major difference between flight demonstration data which is required for aircraft certification, known as “certified data,” and what was used for non-dry operational data, known as “advisory” data. Landing data for snow for instance is considered advisory data as it is not practical to flight test on these conditions during certification nor was there any requirement to do so.

Until the TALPA ARC, the industry had never settled on standard guidelines for creating data for landing on snow, ice, frost, and flooded runways (note: there were data accepted by British UK, JAA and EASA certifications; however, it was not always based on consistent methods or requirements and was not universally accepted). FAA aircraft were certified with no requirement for advisory information. However, often the manufacturer provided data due to non-FAA requirements such as customer support, other certification agency requirements, etc.

Once aircraft are certified and a type design approved for production, the operational aircraft do not include some of the instrumentation that has been added specifically for flight testing. The result is that any braking coefficients determined from these operational aircraft are inferred through a mathematical process of reverse engineering using assumptions applied to flight data normally captured by the aircraft. For official government safety investigations, these assumptions are supplied by the manufacturers who have access to all the parameters used in creating the performance values of the airplane derived from their original flight test. These parameters such as lift, drag, thrust (forward and reverse) is not publicly available.

The TALPA ARC was then faced with three questions.

1. How could aircraft of different types and manufacturers create a standard assessment of the experienced braking performance?
2. How would these assessments relate to ground observations of the runway condition?
3. Could this information be provided to other aircraft operating using a terminology meaningful to everyone?

To answer these questions TALPA ARC needed to add specific engineering values related to aircraft braking to the "matrix" of runway conditions, braking levels, and vehicle observations. This was accomplished in the following manner.

To begin with, the work group assigned specific aircraft wheel braking coefficient values and flight path assumptions to be used in computing time-of-arrival landing distances. The FAA published this information in AC 25-32. The TALPA ARC defined the wheel braking models based on the best-known physics for the runway condition in any given category of braking description (braking action and/or contaminant type) using historical information and testing.

There were two primary model formulations on the resultant braking coefficients accepted for use by the TALPA ARC: a standard model for ground speed dependent braking coefficients and a model utilizing constant braking coefficient values. These two models were based on the best information, generally accepted by industry, resulting from research/testing etc. from the 60's-00's.

Good (wet runway based) and Medium to Poor (slush/standing water based) calculations are based on ground speed dependent modeling. Good to Medium (compact snow), Medium (snow, slippery wet) and Poor (ice) are based on a constant braking coefficient.

These methods were based on a specific engineering concept that related the weight on a specific wheel to the braking force that wheel could produce, known as a wheel braking coefficient. Because these values represented a fraction where the horizontal force produced by a wheel brake was divided by the vertical force being placed on that tire by the aircraft, the result was a non-dimensional number, referred to in engineering parlance as MU or the Greek letter "μ." The range of values the TALPA ARC recommended is shown below with the numbers representing the bottom range of a braking description. For instance, medium braking would lie between a value of 0.199 to 0.16.

Runway Condition Code	**Braking Description**	**Wheel Braking Coefficient**
5	Good	Ground Speed Dependent per §25.109(c)
4	Medium to Good	0.20
3	Medium	0.16
2	Medium to Poor	50% of §25.109(c) Max μ_B=0.16, min μ_B=0.05
1	Poor	0.08

Table 1. AC 25-32 Braking Coefficient Values

Note: These relationships are different than the original relationships defined by Boeing. Figure 2 shows Figure 1 with the calculated braking modified to TALPA relationships (in blue) between braking action and braking coefficient.

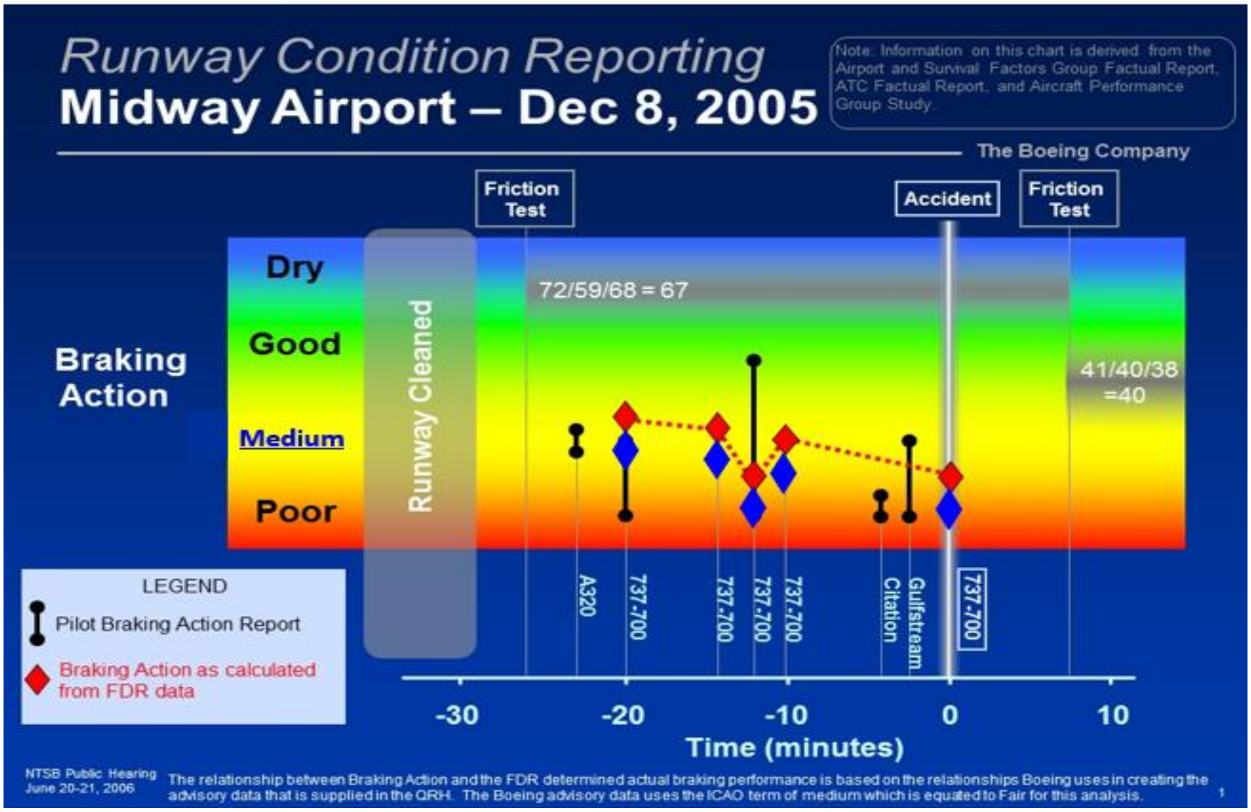


Figure 2 NTSB Public Hearing document modified for TALPA values

It is important to note the above values defined by TALPA were accepted to allow a calculation of ground roll distances to be used in the pilot assessment prior to landing and to ensure all data labeled with the same Runway Condition Code (RCC)/Braking Description was based on the same assumed wheel braking contribution. It is also important to understand that RCC 2, "Medium to Poor," was a compromise level. The practice of using 50% of §25.109(c) values resulted in approximately the same wheel braking as defined by EASA for slush/standing water. The max/min μ_B were included to make sure the answer always stayed between Poor and Medium.

The ARC however *did not* create its initial assessment and quality assurance process *to include wheel brake coefficient data taken off and communicated from operational airplanes*. Because of this it creates challenges when measuring operation braking parameters and working backwards to slot the braking coefficients measured from the airplane to the AC 25-32 values. In the case of a code 2 conditions, (Medium to Poor) the values can cross each other and intersect as shown in figure 3.

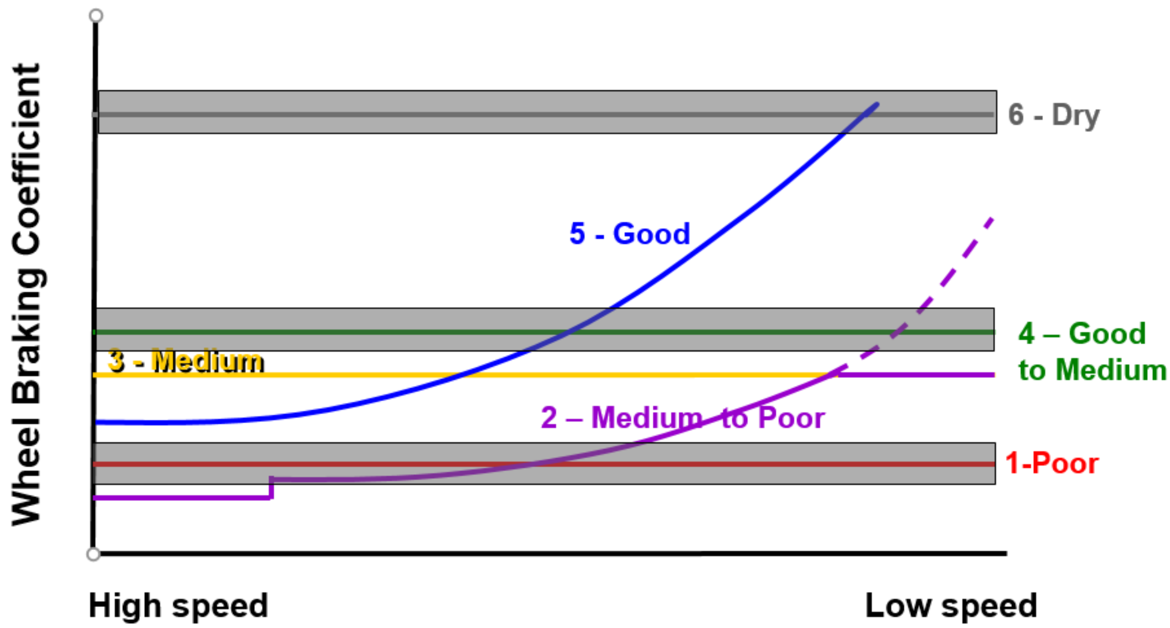


Figure 3 AC 25-32 MU comparison

Combining the NTSB Safety Recommendation, TALPA ARC and FAA Research

The FAA has since instituted research aimed at the previously listed NTSB safety recommendations. One project was sponsored by FAA Airports; the second project was sponsored by FAA Transport Standards Staff. The FAA Airports research concentrated on measuring wheel braking coefficients directly on the airplane for different contaminants. The FAA Transport Standards Staff was aimed at the feasibility of obtaining wheel braking coefficient information from operational aircraft and feeding it back through the system to be used by airports and aircraft operations in making decisions.

Note: the decision process at both the airport and aircraft operations can be broken into *immediate tactical decisions* and *strategic decisions*.

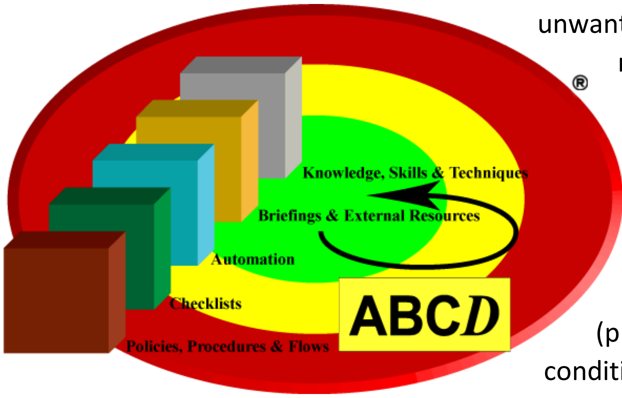
Tactical decisions would include decisions such as; for the airport - does the runway need to be closed or re-evaluated? For the aircraft – does the flight crew need to divert, hold or can it continue the landing?

Strategic decisions would include more prospective actions such as; for the airport – when should the runway be shut for maintenance, contaminant removal, rubber removal etc.? For aircraft – do flights need to be canceled or takeoffs delayed, do additional alternatives need to be considered during dispatch, do arriving aircraft need to be diverted etc.?

Annex III

Risk and Resource Management Concepts

It is an industry best practice that aviation risk be addressed through several layers of mitigations. Most of these consist of objective guidance such as written policies, procedures, checklists, automation, and briefings. These reduce the likelihood that a specific set of conditions will result in the chance of an unwanted outcome. An operator then uses a John Boyd style method of to observe, orient, decide, and act (known as the "OODA loop." The Volant Model, as shown to the left, uses a similar technique by using the letters "ABCD" to represent the terms "assess, balance, communicate and debrief." The intent is for flight crews to continually engage this process throughout a flight and to use the resources available to them (procedures, checklists etc.) to strive to bring them to a condition where errors are less likely to occur.



The recommendations of the group will focus on the ability to provide concrete items for the resources used in such an approach. These resources are aimed at applying to airports, aircrews, and operators as they interact in the real world.

New and Novel Technologies:

ASTM has introduced a standardized set of terminology for use in discussions referencing aircraft braking and performance engineering. To distinguish it from traditional pilot braking reports (PIREPS/AIREPS,) the new term recently published in ASTM Standard E3188-19 is the *Aircraft Braking Report*. This type of report is intended to be the most objective and technically accurate of all TALPA resources.

The capability to assign electronically recorded aircraft braking performance to a TALPA level of braking in a definitive manner can take many forms. They can be informal reference for an operator, a formal procedure for a particular operator, or a standard that is recognized by the industry. At its most effective form, the *aircraft braking report*, used to provide objective information for all transport aircraft who operate under the same assumptions in AC 25-32, would provide standardized risk identification metrics to all stakeholders in the National Airspace System (NAS.) ASTM is currently working on an international standard for such systems so that the process can be transparent and achieve formal acceptance in the industry.

Annex IV

Big Data Analysis

A big data approach to braking performance degradation initiates with subject matter expert guidance into contributing factors to be explored for possible correlation. A representative variance of minimum sample size training set is required for machine learning models to limit bias of the predictions towards certain trained scenarios of braking performance degradation. A non-exhaustive list of dependent factors are categorized as following:

Aircraft:

- Airframe-engine combination
- Fuel bias
- Airframe hours
- Engine hours
- N1 %
- Speed
- Aircraft weight
- Fuel flow
- Autobrake level chosen
- Manual braking level (if applicable)
- Aircraft configuration

Meteorological

- WSR Weather Radar
- ATC Radar
- Airborne Aircraft Radar
- In Ground Pavement Sensors
- Wind speed & direction including gusting
- OAT
- FICON NOTAM (if available)

- METAR
- TAF
- PIREPS (if available)

Runway

- Airport
- Runway
- Runway slope
- Runway density altitude
- Runway material
- ASOS recorded precipitation
- Runway sensor technology

The exploratory data analysis (EDA) phase is documented for replicability and contains data-driven arguments for each independent feature's inclusion in the model. Mathematical metrics including feature correlation, weight, bias and possible collinearity are detailed.

Various models are trained, documented and optimized for accuracy levels and corresponding margin of errors accounting for each condition. Simulated conditions determine the thresholds of the models in normal and abnormal braking performance scenarios prior to final selection of the best model.

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b. NTSB, (2016), ***Safety Recommendation* A-16-023**:
"Continue to work with industry to develop the technology to outfit transport-category airplanes with equipment and procedures to routinely calculate, record, and convey the airplane braking ability required and/or available to slow or stop the airplane during the landing roll."

c. NTSB, (2016), **Safety Recommendation A-16-24:**
"If the systems described in Safety Recommendation A-16-23 are shown to be technically and operationally feasible, work with operators and the system manufacturers to develop procedures that ensure that airplane-based braking ability results can be readily conveyed to, and easily interpreted by, arriving flight crews, airport operators, air traffic control personnel, and others with a safety need for this information."
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