FAA William J. Hughes Technical Center

Aircraft Braking and Runway Friction Research

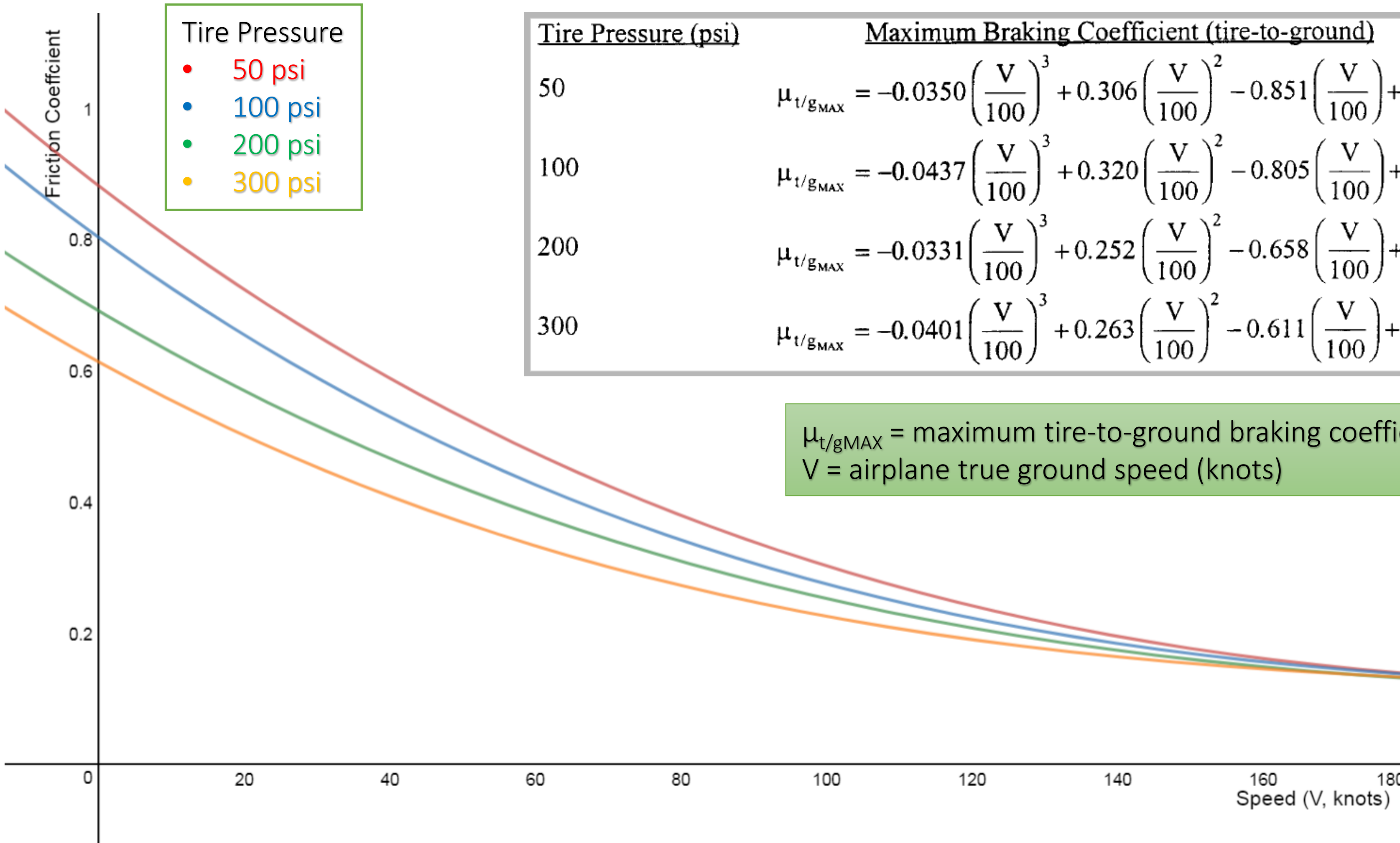
Somil R. Shah | Airports REDAC Meeting | 2-3 March 2021

Background and Motivation

- The accumulation of environmental contaminants decreases the braking friction available between the tire and the pavement, and can significantly increase landing rollout distances
  - Being able to predict when an aircraft has an increased risk of experiencing significantly degraded braking and determining the contributing factors is an important area of research for preventing overruns

- Recent landing overruns on contaminated runways have raised questions regarding the current stopping performance requirements, methods, regulations, and guidance material
  - Existing guidance and regulations make assumptions regarding the braking capability of aircraft landing on contaminated runways, which may not be fully validated in modern operating conditions
  - Aircraft are landing faster and in more marginal airports, elevating the risk of runway overruns if other precursors are present

Current Models – Wet Runway



Tire Pressure (psi)	Maximum Braking Coefficient (tire-to-ground)
50	$\mu_{t/g_{MAX}} = -0.0350\left(\frac{V}{100}\right)^3 + 0.306\left(\frac{V}{100}\right)^2 - 0.851\left(\frac{V}{100}\right) + 0.883$
100	$\mu_{t/g_{MAX}} = -0.0437\left(\frac{V}{100}\right)^3 + 0.320\left(\frac{V}{100}\right)^2 - 0.805\left(\frac{V}{100}\right) + 0.804$
200	$\mu_{t/g_{MAX}} = -0.0331\left(\frac{V}{100}\right)^3 + 0.252\left(\frac{V}{100}\right)^2 - 0.658\left(\frac{V}{100}\right) + 0.692$
300	$\mu_{t/g_{MAX}} = -0.0401\left(\frac{V}{100}\right)^3 + 0.263\left(\frac{V}{100}\right)^2 - 0.611\left(\frac{V}{100}\right) + 0.614$

$\mu_{t/gMAX}$ = maximum tire-to-ground braking coefficient
V = airplane true ground speed (knots)

Example of Wet Runway Issues

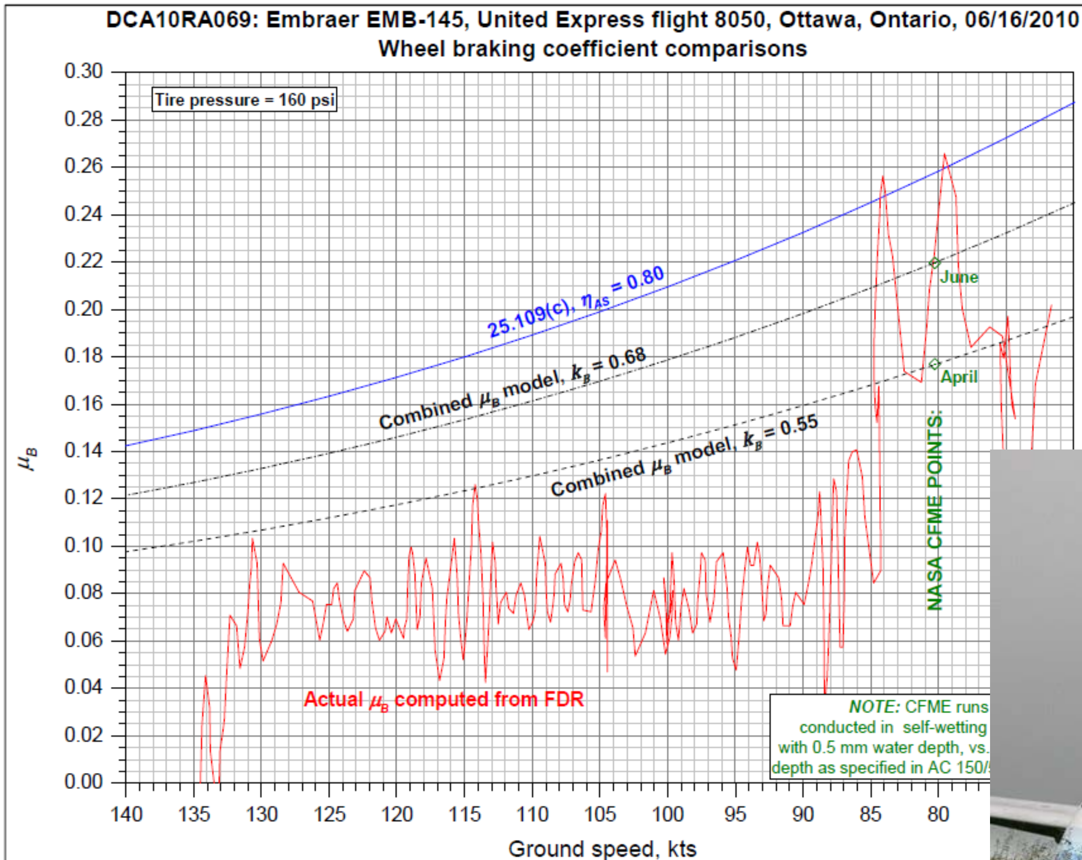


Figure 15. μ_B comparisons for the United Express flight 8050 accident in Ottawa, Ontario, 06/16/2010.

NTSB Recommendations

- *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.

- *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.

- 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).

Airports/Tech Center Work Using B727

- Direct measurement of wheel braking through the attachment of strain gauges
- Aircraft not airworthy – limited to ground testing up to a certain ground speed

- <u>Objectives</u>
  1. What friction levels can be achieved in winter weather conditions?
  2. What methods can be used to quantify friction levels?
  3. What is the behavior of anti-skid systems in these low friction conditions?
  4. What items can civil transport aircraft measure, or be equipped to measure, to determine the available friction level?

Current Work – Research Questions

- The friction available between a tire and the runway depends on many different variables, such as *ground speed*, *tire inflation pressure*, *rainfall intensity*, and *pavement texture/grooving*

- Which variables have the largest effect on aircraft wheel braking and under what conditions may an aircraft experience significantly reduced wheel braking compared to current models?

- Is it possible to predict the wheel braking capability to be expected for an aircraft about to land on a contaminated runway and provide such information to the flight crew to aid decision-making?

Involved Organizations

Aviation Research Division

Software and Systems Branch

(ANG-E27)

- Research requirement to conduct wet runway wheel braking flight testing
    - ~$1.8M funding
- Machine learning effort with Georgia Tech
    - Airports provided ~$300K of funding

Airport Technology Branch

(ANG-E26)

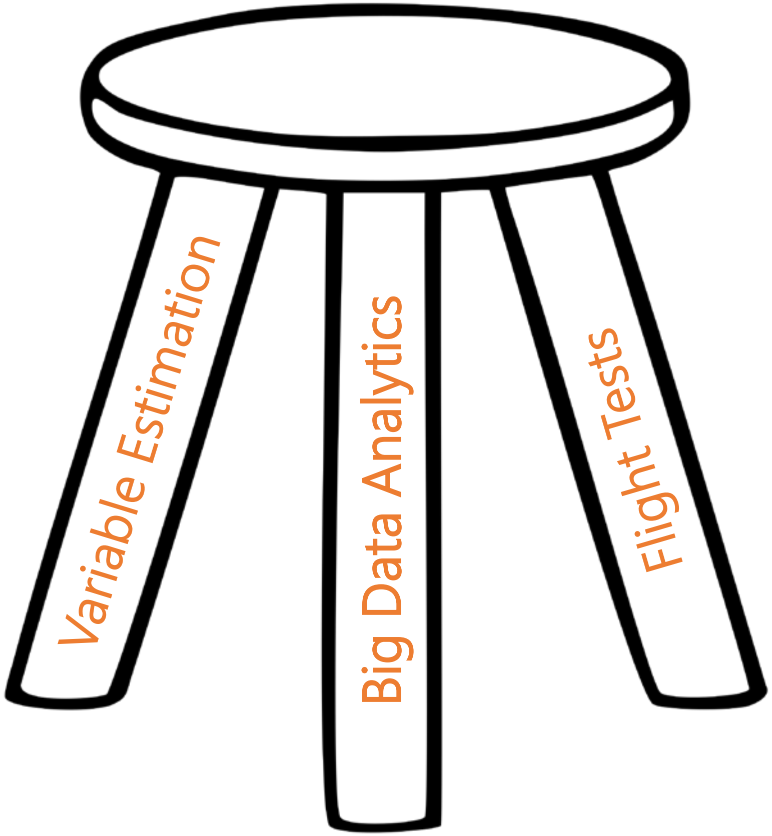
- Past work using Boeing 727 (R&D 40) for runway friction research
- Evaluating trapezoidal grooving
    - Flight testing
    - Finite element modeling (Rutgers University)
- Machine learning effort with MIT
- Planning drainage experiments
- ~$300K dedicated for aircraft braking and runway friction

High-Level Research Plan

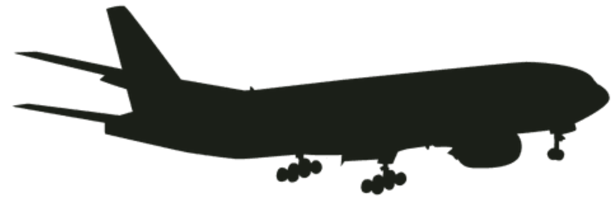
- The problem is complex – many different variables which are difficult to acquire, measure, and/or control
    - Historically, things were made simple or not considered at all
    - Today, we have the ability to measure more variables to more detail and analyze more data to higher complexity

- The research team believes that multiple, complementary studies are required

- Primary efforts have been divided into three main components:
    - Physical flight testing
    - Machine learning
    - Variable estimation/drainage studies



Flight Testing

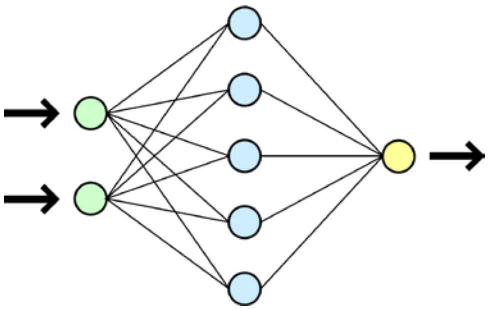


- Purpose: *acquire high-fidelity data* to determine contributing factors for significantly reduced wheel braking on contaminated runways and determine the relationships between them and the underlying physical principles

- Contracted with Enroute Computer Solutions (ECS) to lease an aircraft and conduct flight tests at ***NASA Wallops Flight Facility*** where water depths can be closely monitored and controlled
  - Completed phase 1 of effort involving the completion of a flight test plan and coordination with NASA Wallops
  - Evaluating phase 2 proposal involving execution of flight test plan and data analysis
  - Following phase 2, make recommendations for future work and on updating models, standards, guidance material, etc.

- Limitations: flight testing is expensive, logistically complicated, takes time, and limited in scope, so what else can we do?

Machine Learning

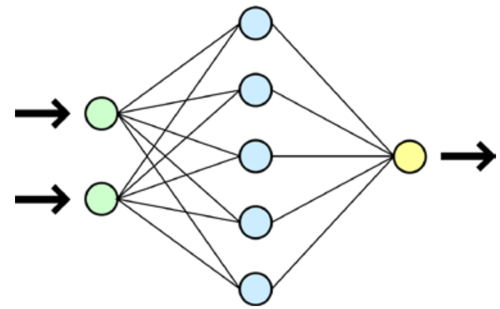


- The research team has also been exploring the use of *machine learning* to complement flight testing efforts through academic partners

- Premise: use readily available *big data* (aircraft, weather, NOTAMs, etc.) to *identify* degraded braking, *determine contributing factors*, and *predict* when degraded braking may occur – exploratory research

- Collaborating with MIT and using data from *Aviation Safety Technologies (AST)*: real-time analysis of aircraft braking thanks to aircraft-based sensors
  - Database of 4.9 million landings between Feb 2017 and Jun 2019
  - Data fused with pilot braking action reports, weather conditions, runway parameters, etc. to determine relationships
- Also collaborating with Georgia Tech, using aircraft data from a partner airline
  - *Many datasets are being fused and analyzed holistically that have not been combined in this way before*

MIT Machine Learning Approach



What is performance? (Truth data)

- **Pilot Braking Reports**
- **Aviation Safety Technologies (AST) sensor data**

Which landing conditions? (features)

- **Weather**
- **Runway contamination**
- **Aircraft parameters**
- **Runway surface & geometry**

Modelling

- Using Machine Learning classifiers of different levels of complexity:

1. **Random Forest**
2. **Artificial Neural Net**

Feature importance

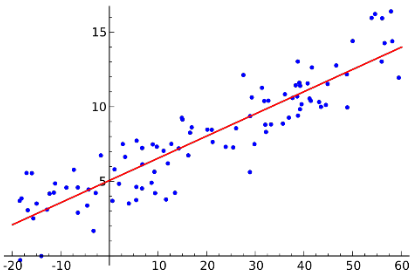
- Using model specific methods to infer relative importance of features

Evaluation

- Is the model performing well? (accuracy, AUC, sensitivity)
- What can be done to improve performance?

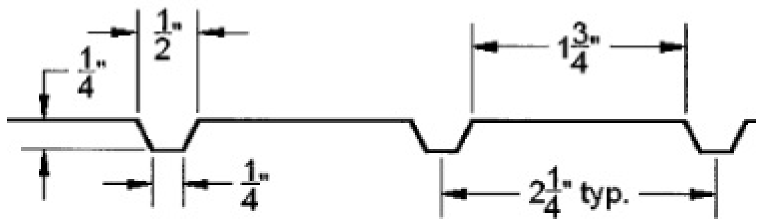
Iterative process – results of initial, exploratory machine learning work will influence and guide future machine learning work as well as flight testing and variable estimation efforts

Variable Estimation



- Purposes: (1) learn to measure, control, and/or estimate relevant variables for testing purposes, and (2) validate existing drainage and water depth models
- Gather pavement properties: friction (CFME) values, pavement surface texture readings (micro- and macro-texture), etc. and ***determine how variables are related***
- With the addition of cross slope, possibly procure rain simulation equipment and run at various rainfall intensities to evaluate film thickness (water depth) models
- Drainage model may be useful for machine learning efforts described on the previous slide

Trapezoidal Grooving

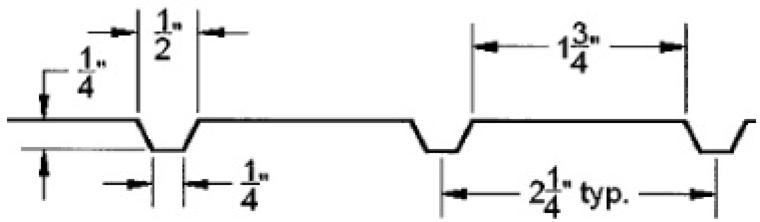


- Purposes: assess the performance of trapezoidal-shaped runway grooving relative to FAA Standard Grooving for maintaining skid-resistance and preventing hydroplaning

- Research Path: (1) develop finite element models for simulating aircraft tire-water-pavement interaction with both trapezoidal shaped and FAA Standard Grooving, and (2) develop reduced-scale laboratory test platform for simulating aircraft braking on wet pavement conditions with both trapezoidal shaped and FAA Standard Grooving

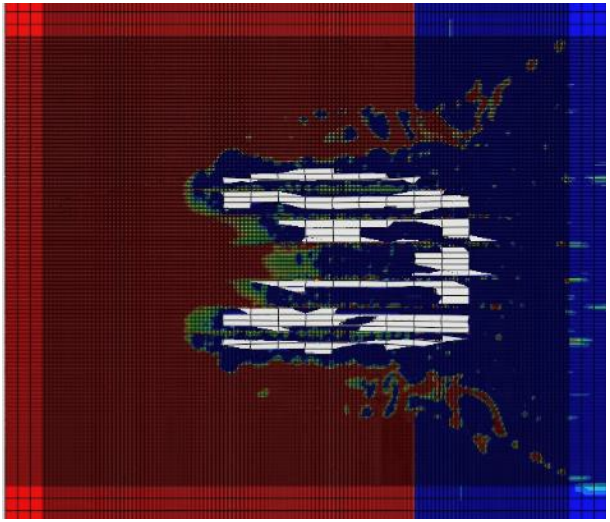
- Research effort currently being conducted by staff at Rutgers University

Trapezoidal Grooving Status

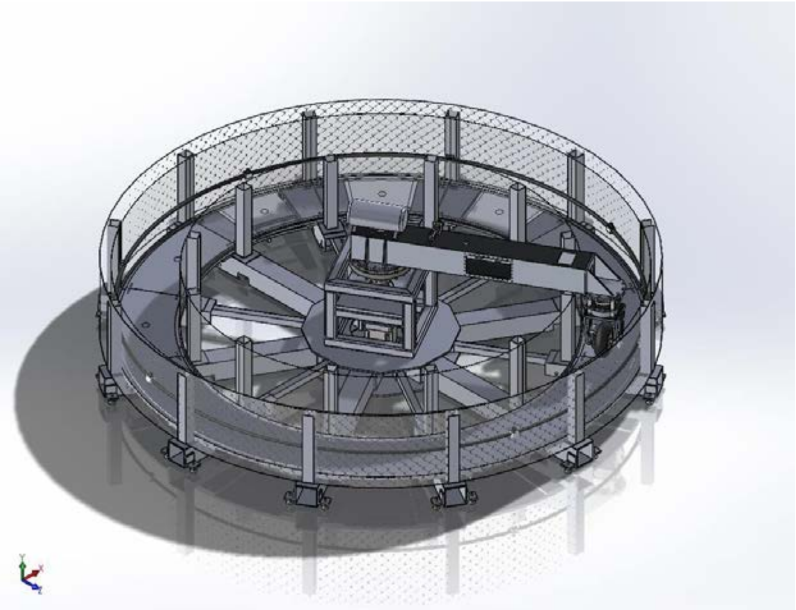


- Two different simulation models were created to look at the interactions of an aircraft tire and a water surface

- Test platform design has been finalized and currently under construction



Water penetration into tire contact patch at 140 knots



Concluding Remarks

1. Contaminated runway wheel braking research is inherently complex and very multidisciplinary

2. Historically, a number of simplifications and assumptions were made to make things work, and they did for the most part, but as the limits of air travel are being pushed, such simplifications may not hold true in certain modern operating conditions, motivating the need to reassess and potentially update current models and regulatory/guidance material

3. The research team believes that a multi-faceted approach is needed, involving a mix of full-scale testing and machine learning

4. Current work primarily revolves around wet runway wheel braking, although applications to other contaminants are being considered wherever possible

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Questions and Discussion

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Backup Slides

Some Terminology

- **Wheel Braking Coefficient** – ratio of deceleration force from braked wheels relative to the sum of the normal forces acting on the wheels
- **Aircraft Braking Coefficient** – ratio of the deceleration force from the braked *and unbraked* wheels relative to the sum of the normal force acting on the aircraft
- **Tire-to-Ground Friction Coefficient** – deceleration force of a single tire divided by the normal force on that tire
- **Maximum Tire-to-Ground Friction Coefficient** – the highest amount of wheel braking achievable given tire, pavement, and environmental conditions
- **Pilot Braking Action Report (PIREP)** – qualitative assessment of the slipperiness of the runway made by assessing the deceleration of the aircraft relative to the amount of brake pressure commanded

Some More Terminology

- Slip Ratio – one minus the ratio of the circumferential speed of a rotating wheel to it's translational speed.
  - = 0 (freely rolling)
  - = 1 (locked wheel)
- Mu-Slip Curve – relationship between slip ratio and the tire-to-ground friction coefficient
- Anti-Skid System Efficiency – percentage of the maximum tire-to-ground friction coefficient that an anti-skid system is able to achieve
- Friction Limited Condition/Braking – a wheel braking condition where the ability of the brakes to supply a decelerating force is limited by amount of friction available given tire, pavement, and environmental conditions