Improving Runway Pavement Friction Analysis through Innovative Modeling

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INTRODUCTION

Available runway friction has a significant impact on aircraft landing performance. This is especially noted when aircrafts are landing on wet or otherwise contaminated runways due to the reduced braking action, which has been well documented since the dawn of the jet aircraft age. In addition, according to International Air Transport Association (IATA) statistics, runway excursions contribute nearly a quarter of all the accidents and no trends show an obvious decrease of these accidents in the past few years [1-4]. In order to prevent runway landing excursion accidents and incidents, and enhance airport and airline operation safety, available runway friction should be studied.

A good level of available runway friction is required for aircraft landing operations [5]. With the presence of water film, snow, and ice, the available runway friction changes rapidly, and different measure devices provide results with a large variance on a uniform runway condition [5]. According to the results of a survey of Canadian airline pilots in the Joint Winter Runway Friction Measurement Program, “Pilots indicated that the quality of runway friction information provided by airports varies between airports. Generally the quality is better at large airports, but each airport differs depending on various factors” [6]. Because of the inconsistences in runway friction measuring devices, it is better to analyze available runway friction based on aircraft measurements. In order to model the aircraft’s landing performance, a mechanistic-empirical aircraft landing deceleration equation has been developed [7]. This equation incorporates all of the major forces that contribute to aircraft braking, and was calibrated and validated using digital flight data from dry runway aircraft landings. As a result, it is able to back calculate friction from the developed equations and evaluate the impacts of dry, wet, and contaminated runways on aircraft braking performance.

The objectives of the paper as follows:

- Provide back ground knowledge regarding wet and contaminated runway aircraft braking;
- Analyze aircraft braking performance on wet and contaminated runways using the built mechanistic-empirical aircraft landing deceleration equation; and
- Study runway available braking friction under different conditions.

BACKGROUND

Factors Affecting Runway Friction

Friction force is influenced by a combination of aircraft tires, aircraft braking systems, and airport runway pavement surfaces [8]. Studies on these three aspects have been conducted; and NASA had some significant achievements in the 1960s [9-11].

The following listed factors are the main factors affecting runway friction [12]:

- Ground Speed;

- Slip Ratio;
- Tire texture and inflation pressure;
- Pavement texture; and
- Water or contaminations.

Braking Pressure Performance

Friction force has two parts: the rolling resistance force and the slip resistance force [13]. When the tire is free rolling, only a rolling resistance force is applied on the wheel. As braking is applied, a slip occurs between the tire and the pavement surface. As shown in Figure 1 [13], the tire proceeds from free rolling to a locked wheel, the coefficient of friction varies with the changes of the tire slip. The coefficient of friction increases rapidly from a certain value, which is referred as rolling resistance coefficient, to a peak friction value and then it decreases to another certain value, which is referred as slide resistance coefficient [13, 14]. The peak friction usually occurs when the tire slip is between 10% to 20% slip, which is known as the critical slip. When the slip proceeds to 100% slip, which means the wheel is fully locked, the coefficient decreases to a slide resistance friction coefficient. The slip resistance friction is lower than the peak friction. The difference between the slip resistance friction and peak friction is bigger for wet and contaminated pavements than dry pavements [13].

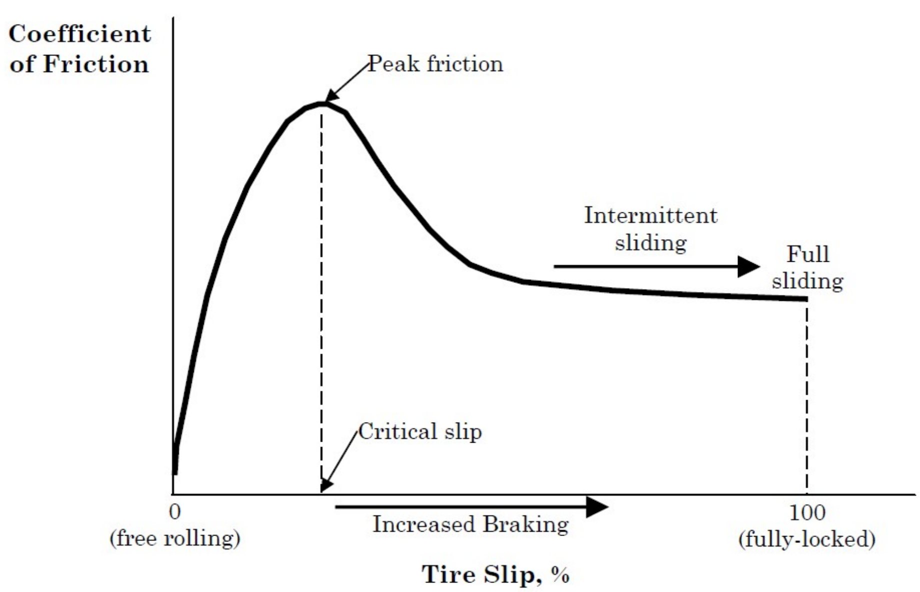


Figure 1. Pavement Friction vs Tire Slip [13].

The aircraft braking system is braking pressure controlled. The function of the anti-locking brake system installed in the aircraft is to control the braking pressure to achieve a tire slip to reach a friction near the peak friction. When peak friction is achieved, the Anti-locking brake systems will not increase braking pressure, or even release the brake for a short time. More braking pressure will be applied when peak friction is not reached [13, 14].

In the study of Zhang et.al. [7], four major sources of forces contribute to aircraft deceleration were considered to analyze aircraft deceleration. The forces are aerodynamic drag force, engine thrust/reverse thrust, friction force, and the parallel component of gravity generated by the slope of the runway (Figure 2). Based on the mechanistic equations for aerodynamic drag force friction force, and the parallel component of gravity, and empirical calibrated equation for engine thrust/reverse thrust, an aircraft deceleration equation is built. The equation has several aircraft characteristic adjustment coefficients that are calibrated with digital flight data and airport weather data. After calibration the equation can provide an accurate prediction of aircraft deceleration. The equation is given as follow, which is referred as the M-E aircraft deceleration equation [7].

$$a = \frac{D+R+F+S}{m} = a_1 \cdot \frac{\rho_{air} V^2}{m} + a_2 \cdot \frac{f(TLA)}{m} \cdot n_E + a_3 \cdot \frac{BP}{m} \cdot n_w + g \cdot \sin\varphi \quad (1)$$

where: D is the aerodynamic drag force; R is the engine thrust/reverse thrust; F is the friction force; S is the parallel component of gravity; n_E is engine numbers; n_W is the landing gear wheel numbers; a_1 is the aircraft aerodynamic drag force adjustment coefficient; a_2 is the aircraft engine thrust/reverse thrust adjustment coefficient; and a_3 is the aircraft friction force adjustment coefficient.

"Aircraft characteristic adjustment coefficients (a_1, a_2, a_3) are determined by the linear regression using flight data and weather data. Once they are established, the calibrated empirical equations for aerodynamic drag force, engine thrust/reverse thrust, and friction force are identified." [7] So based on Equation 1, a mechanistic-empirical aircraft friction equation can be identified as Equation 2. The equation is under the condition that peak friction is not achieved. The equation provides an opportunity to analyze aircraft braking performance.

$$Friction = \mu \cdot G = a_3 \cdot BP \cdot n_w \quad (2)$$

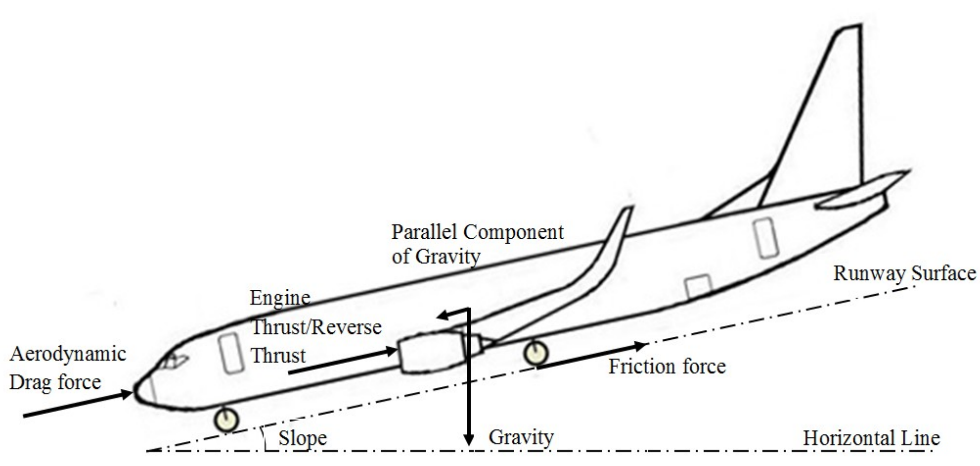


Figure 2. Aircraft Free Body Diagram [7].

METHODOLOGY

The overall research methodology of this paper is shown in Figure 3. First, digital flight data, airport runway condition monitoring data, and weather data are collected, and retrieved as the data source. According to airport runway condition monitoring data and weather data, all the data are classified into three categories: dry runway data, wet runway data, and contaminated runway data. Seventy-five percent of the dry runway landing data is used to calibrate the mechanistic-empirical (M-E) aircraft deceleration equation. The remaining 25% data is used to validate the calibrated equation and study dry runway braking performance. Based on the mechanistic-empirical aircraft deceleration equations, wet runway braking performance and contaminated runway braking performance can be analyzed. By comparing dry runway, wet runway, and contaminated runway braking performances, aircraft landing braking action's limitations with respect to frictional properties of runways under different conditions are analyzed.

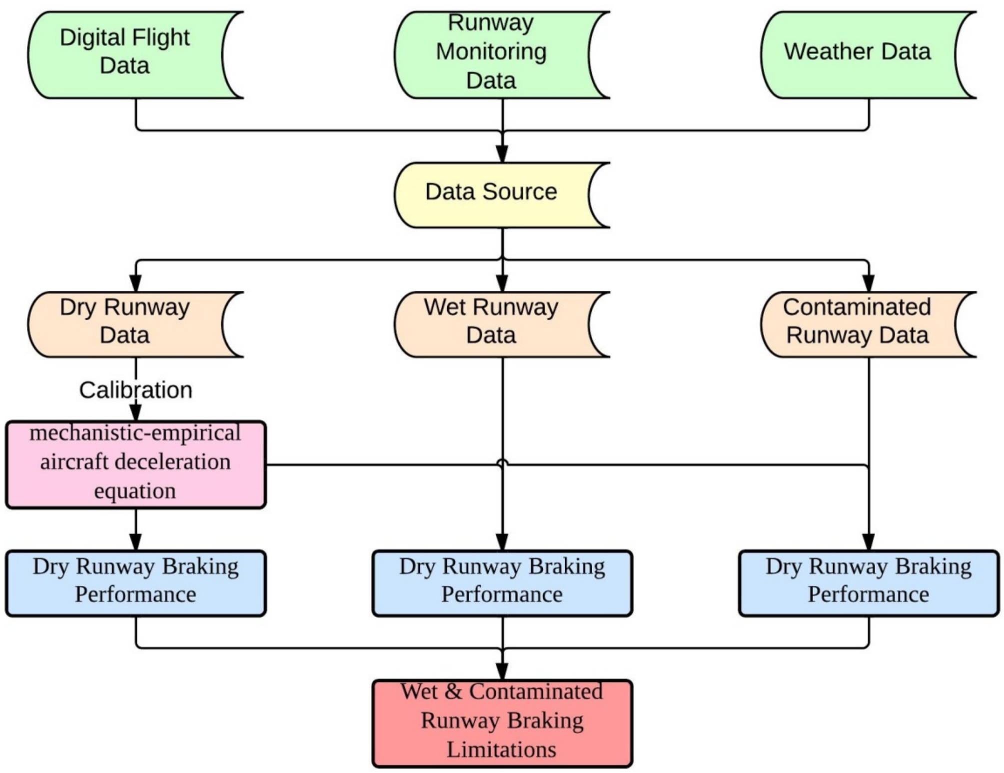


Figure 3. Overall Methodology.

RUNWAY PAVEMENT FRICTION ANALYSIS

The relationship between braking friction coefficient and braking pressure can be described as Figure 4. It is assumed that for a landing gear, the achieved braking friction coefficient is a linear function of braking pressures before the peak braking friction coefficient is reached. The coefficient is a unique value for the specific landing gear. For different runway pavement condition, the peak friction is different, for wet or contaminated runway the peak friction is smaller than dry runway. Under wet or contaminated condition, a lower braking pressure will result in a locked wheel.

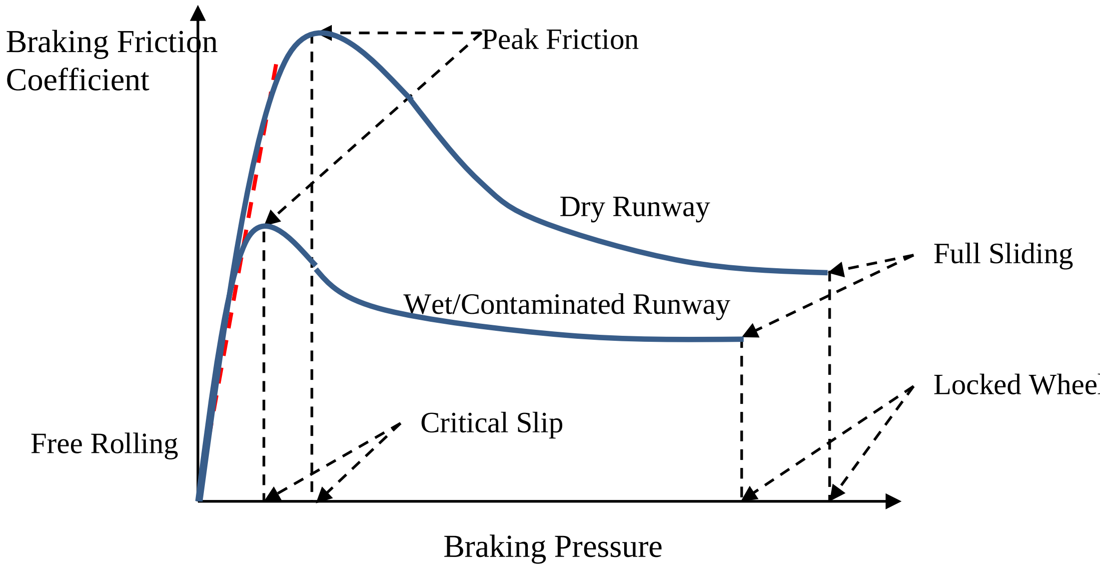


Figure 4. Braking Friction Coefficient vs Braking Pressure.

$$\mu = a_3 \cdot \frac{BP}{mg} \cdot n_w \tag{3}$$

$$F = am - a_1 \cdot \rho_{air} V^2 - a_2 \cdot f(TLA_1) - g \cdot sin\,\varphi \tag{4}$$

$$\mu = \frac{am - a_1 \cdot \rho_{air} V^2 - a_2 \cdot f(TLA_1) - g \cdot \sin\varphi}{mg} \tag{5}$$

Equation 3 is derived from the mechanistic-empirical (M-E) aircraft friction equation with the input of aircraft characteristic adjustment coefficient and the braking pressure, which represents the red dashed line in Figure 4.

Equation 4 and 5 are derived from the M-E aircraft deceleration equation with the input of air density aircraft speed, thrust settings, aircraft deceleration rate, and the slope of the runway. Equation 4 and 5 are used to back calculate the friction and braking friction coefficient with digital flight data.

The M-E aircraft deceleration equation assumed a linear relation between applied braking pressure, a known value, and friction, unknown, to model the frictional forces (before it researches the peak friction). According to Equation 5, the friction force is a function of the entire deceleration, air density, velocity, TLA setting, weight of the aircraft, and the slope of the runway pavement. Based the calibrated M-E deceleration, the friction from the runway can be back calculated.

In this paper, the aircraft friction force adjustment coefficient for each landing gear is calibrated. The tire inflation pressure is one of the landing gear characteristics, and the adjustment is included in the aircraft friction force adjustment coefficient. Since all of the data is collected from an asphalt runway pavement, the pavement texture is not studied in this research. In this analysis, aircraft braking performance is studied regarding the relationship between aircraft speed and braking friction coefficient as well as the relationship between braking pressure and braking friction coefficient.

Data Collection

The sources of data used in this research are shown in Table 1.

Table 1
Data for M-E Model

Data Type	Sources of Data
Flight Data	Digital Flight Data Recorder installed in a WestJet Boeing 737-700 aircraft
Runway Data	Waterloo International Airport runway monitoring system.
Weather Data	University of Waterloo's Weather Station Environment Canada

After flight data calibration, the equation for the mechanistic-empirical deceleration and friction for the WestJet Boeing 737-700 aircraft is given as follows.

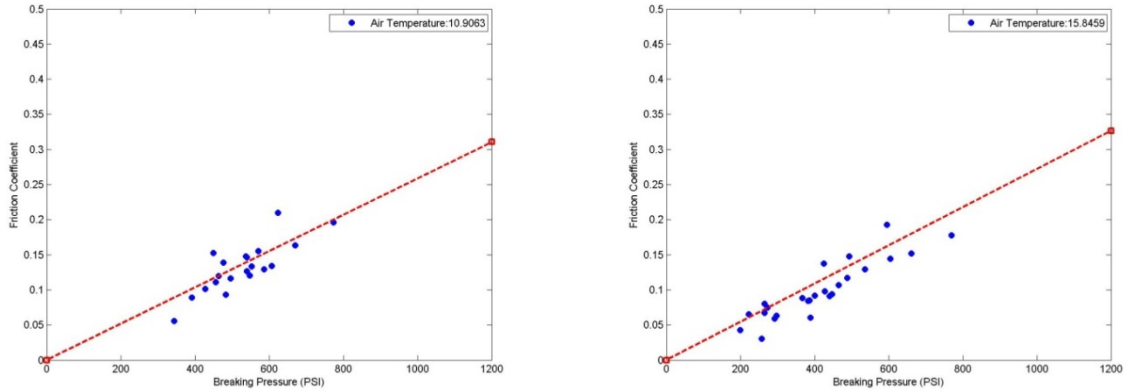
$$a = 0.0024 \cdot \frac{\rho_{air} V^2}{m} - 49.555 \cdot \frac{f(TLA)}{m} \cdot n_E + 0.0699 \cdot \frac{BP}{m} \cdot n_w + g \cdot \sin\varphi$$

$$Friction = \mu G = 0.0699 \cdot BP \cdot n_w$$

where: n_E is Engine numbers; n_W is the landing gear wheel numbers; a_1 is the aircraft aerodynamic drag force adjustment coefficient; a_2 is the aircraft engine thrust/reverse thrust adjustment coefficient; and a_3 is the aircraft friction force adjustment coefficient.

Dry Runway Braking Analysis

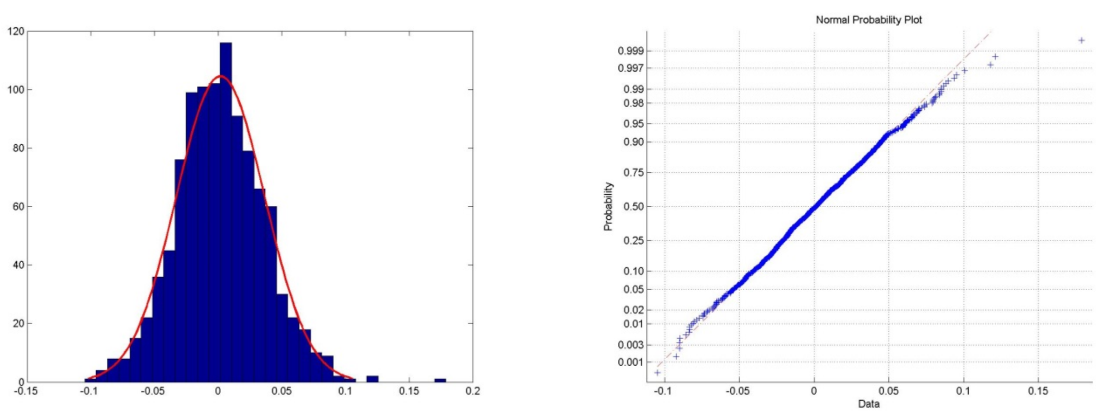
In Figure 5, the X-axis is the braking friction coefficient, and the Y-axis is the braking pressure. Figure 5 shows the results of two dry runway landing. Each blue point represents a back calculated braking friction coefficient using a data point collected during landing. The red line is the calibrated M-E aircraft friction equation, which also represents the red dashed line in Figure 4. The blue points locate along the red line. The location and distribution of the points are influenced by the pavement condition. Figure 5 indicates that for the given two flights, the runway condition is good and can provide sufficient friction for braking.



(a) (b)

Figure 5. Braking Friction Coefficient vs Braking Pressure, Dry Pavement.

Due to the non-uniform nature of the pavement surface texture and the associated properties, the point could vary along the red dashed line. Although the pavement surface texture and its properties have an impact on the variance of the location and its distribution, the variance should remain in a certain range of value. Figure 6 (a) is the histogram of the difference between the back calculated braking friction coefficient and calibrated M-E aircraft friction equation for 75% of the dry runway data. Figure 6 (a) is the normal probability plot. Both of the figures indicate the differences follow normal distribution. The mean value of the distribution is -3.86×10^{-4}, and the standard error is 0.03. So the 90% confidence interval is -0.057 to 0.057.



(a) (b)

Figure 6. Histogram and Normal Probability Plot, Dry Pavement.

Wet Runway Braking Analysis

The water on the pavement will reduce the frictional property of the runway. In addition, a layer of water which lies between the aircraft tire and the landing pavement surface will generate a lift force. When the lift force equals to the weight of the aircraft, hydroplaning will occur. If hydroplaning occurs, the aircraft is lifted and there is little friction between the aircraft tire and the runway surface. In this case, the landing gear is locked due to inefficient friction and could lead to an unsafe situation. Figure 7 is a free body diagram of a landing gear wheel on wet runway pavement when hydroplaning happens.

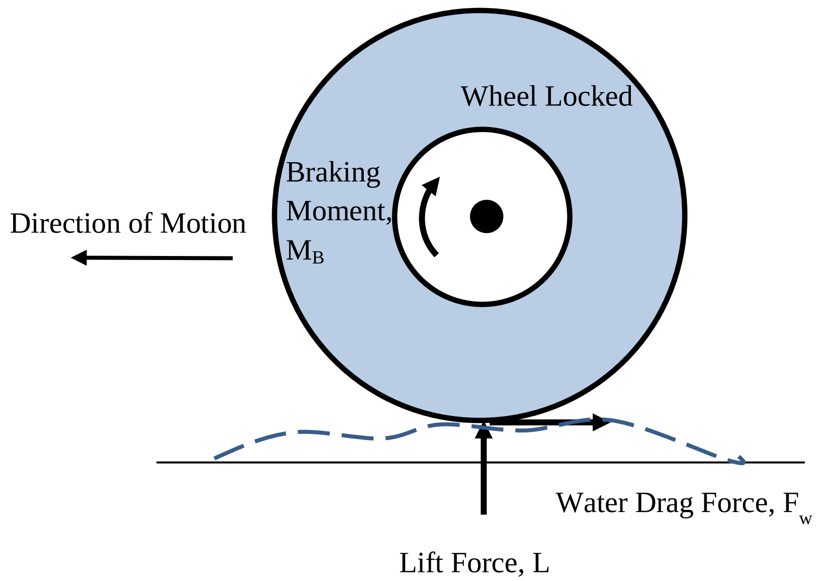
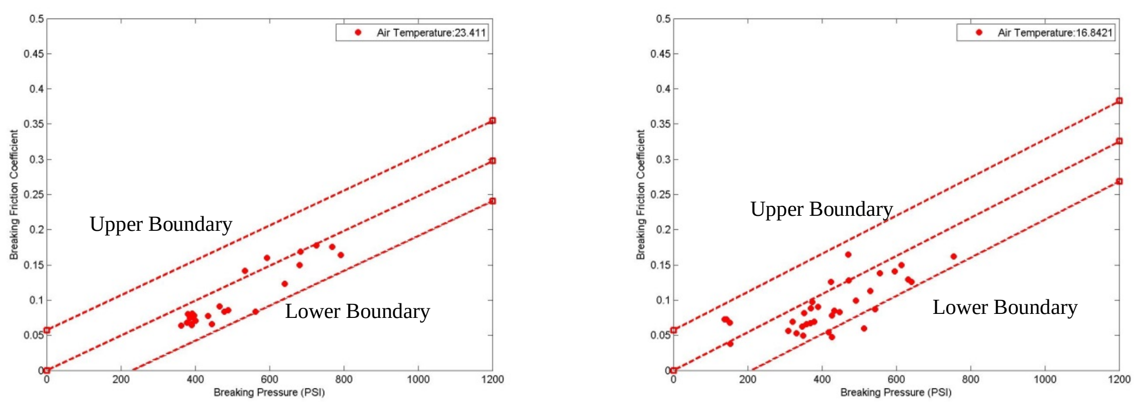


Figure 7. A Hydroplaning Landing Gear Wheel on Wet Runway Pavement.



(a) (b)

Figure 8. Braking Friction Coefficient vs Braking Pressure, Wet Pavement.

Figure 8 shows the results of two wet runway landing. Each red point represents a back calculated braking friction coefficient using a data point collected during landing. The centered red line in Figure 8 is the calibrated M-E aircraft friction equation and the top and bottom red lines are the 90% confidence boundaries. The red points located along the red line and within the top and bottom boundaries.

Figure 9 (a) shows the results of 21 wet runway landings. Most of the points located within the 90% confidence interval, which indicates that during these 21 flights, wet runway remains a good runway friction condition which is similar to the dry runway pavement findings.

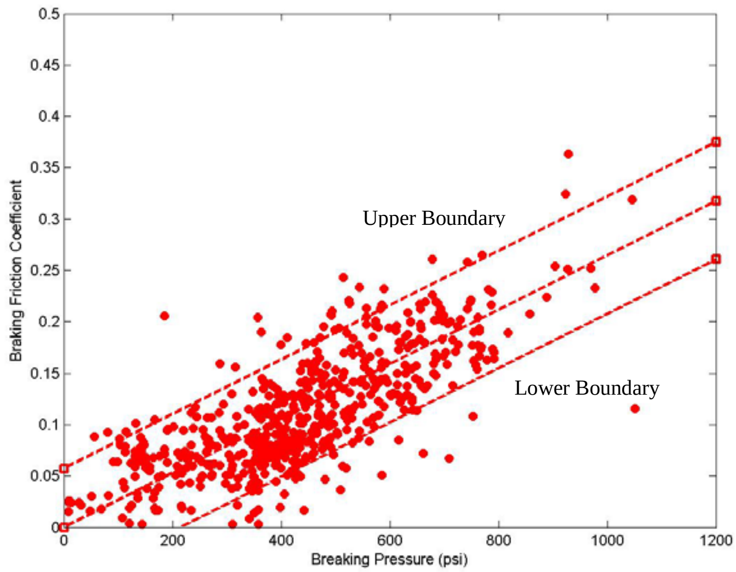


Figure 9. Braking Friction Coefficient vs Braking Pressure.

The red points below the bottom red line represent that in that location the tire does not achieve the expected friction force. The possible reasons for these occurrences are:

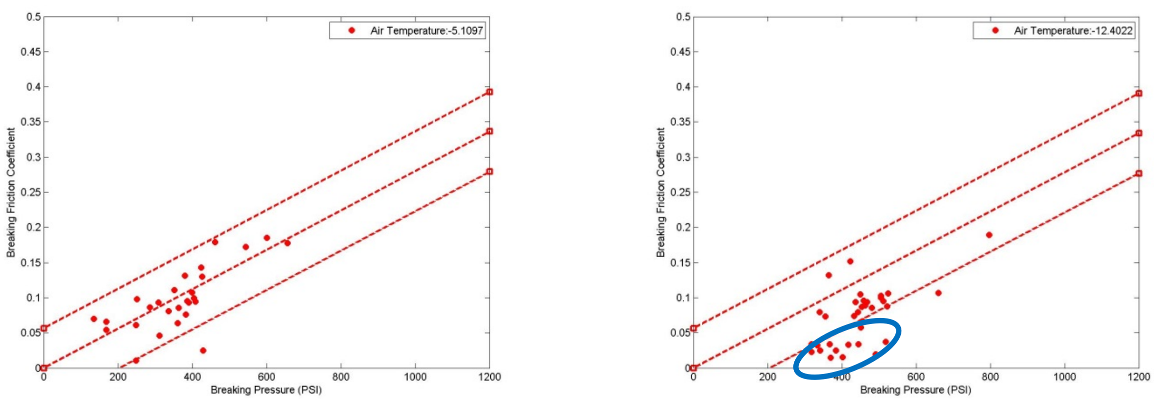
- Hydroplaning. When hydroplaning occurs, the aircraft is lifted and does not touch the pavement surface, so the braking friction is almost zero. Hydroplaning can happen just for a very short time slot, because of the aircraft anti-locking system.
- Poor friction. Some poor frictional prosperity area may exist because of poor pavement surface texture or contaminants on the runway such as dust on the pavement surface and standing water.
- Error data points.

Contaminated Runway Analysis

A contaminated runway is a runway with “standing water, slush, snow, compacted snow, ice or frost covering more than 25% of the required length and width of its surface [15]”. The presence of contaminants on the runway reduces the friction between the tire and runway surface. The reduction is a function of several factors including the tire-pavement interaction, the anti-locking system performance, type of runway pavement, and the type of contaminants. The contaminants can contribute to aircraft deceleration by applying a drag force against the motion of moment. However, the drag is relative small compared to the reduction of friction between the tire and runway surface. Also, the contaminants may cause damage to the landing gear wheel.

Figure 10 (a) presents the back calculated data from a landing on a runway with a condition of “90 % BARE AND DRY, 10 % BARE AND WET” and Figure 10 (b) is from a runway of “40 % BARE AND DRY, 60 % DRY SNOW TRACE.”. The circled points in Figure 10 represent the situation that the aircraft achieves a friction that is below the average friction value which it is supposed to generate. It indicates that the contaminants have a significant influence on aircraft braking. The more contaminants on the runway, the greater reduction in friction will be. However, it should be noted that a small amount of contaminant on the runway can still result in a good frictional value. This is most likely related to the fact that the Waterloo International Airport ensured the runway is maintained to a high level of service. The runway condition is good, so insufficient friction braking did not occur in the collected data. Figure 10 (b) shows the worst case in the collected data.

The possible reason for the occurrence of the circled points in Figure 10 (b) is contaminants. The snow on the pavement may reduce the frictional property of the pavement or separate the tire and pavement surface.

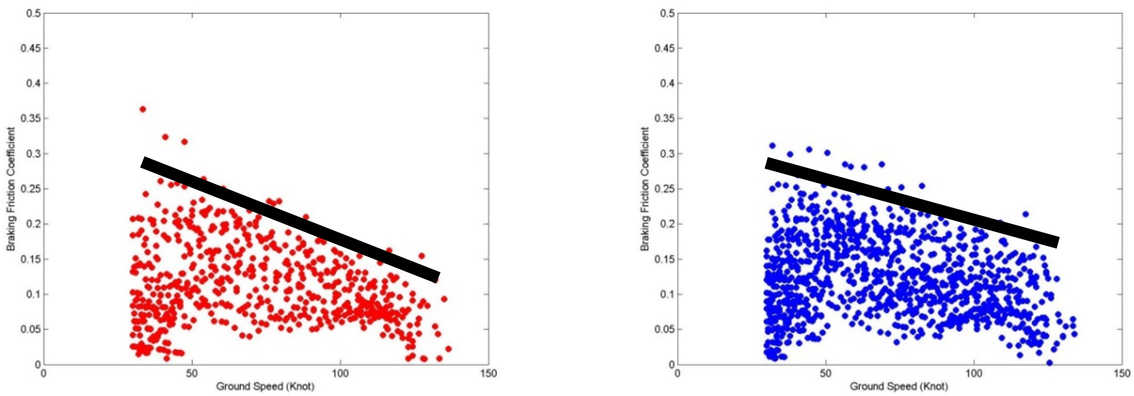


(a) (b)

Figure 10. Braking Friction Coefficient vs Braking Pressure, Contaminated Runway.

Braking Friction Coefficient under Different Speed

The relationship between braking friction coefficient and aircraft ground speed is shown in Figure 11 Braking Friction Coefficient under Different Speed Since all data is from a commercial aircraft, maximum braking is not used for all the collected flights. It is assured the highest back calculated braking friction coefficient value for each speed is the maximum available braking friction coefficient for that speed. Due to the big variances, some of the data points are considered error points. The red points in Figure 11 (a) are the back calculated braking friction coefficient when the runway is wet. The blue points in Figure 11 (b) are the back calculated braking friction coefficient when the runway is "Bare and Dry 100%". The speed of analyzed data is in the range of 30 knots to 135 knots. The results indicate that when the speed is low, the wet runway have a maximum available braking friction that is nearly the same as the dry runway. With the speed increases, the maximum available braking friction decreases for both wet runways and dry runways. However, a bigger drop in maximum available braking friction occurs when the runway is wet.



(a) (b)

Figure 11 Braking Friction Coefficient under Different Speed

CONCLUSIONS

In this paper, wet and contaminated aircraft braking are provided, and a method to analyze aircraft braking on wet and contaminated runways using a novel M-E aircraft landing deceleration equation is introduced. Digital flight data from a Boeing 737-700, runway pavement condition monitoring data, and weather data are collected and a study of a Boeing 737-700 aircraft landing on dry and wet runway is conducted. The key findings of this paper are as follows:

- If well maintained, wet runway does not reduce braking performance significantly.
- Contaminated runways have larger impact on braking performance than wet runway.
- Available braking friction coefficient is ground speed depended. With the speed increase the available braking friction coefficient decreases. And wet runway available braking friction coefficient is more depended on speed and decrease faster than dry runway.

FUTURE WORK

Since all the collected in this research in from a commercial aircraft that did not use full braking for all the flights and Waterloo International Airport maintain its runway rapidly in a good condition, hydroplaning and insufficient friction braking due to contaminants did not occur in the collected data. Future aircraft landing test on runways with severe wet and contaminated conditions are recommended. In addition, full braking or max braking landing test are also recommended to analyze the available braking friction. In this research, runway roughness is not considered. However, its influence on runway braking should be conducted in the future study.

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