XXI SITRAER
2024 | Air Transportation Symposium

ASSESSING THE IMPACT OF AIRCRAFT LANDINGS ON RUNWAY FRICTION VARIATION AT BRAZILIAN AIRPORTS

Tiago Silveira de Andrade Aquino, José Wémenson Rabelo Chaves, Francisco Heber Lacerda de Oliveira
Universidade Federal do Ceará, Departamento de Engenharia de Transportes

*** Corresponding author e-mail address**: tiago.silveira@det.ufc.br;

PAPER ID: SIT887651

ABSTRACT

This study evaluates the relationship between the temporal variation of runway friction coefficients and the number of aircraft landings at selected Brazilian airports. Data were collected from National Civil Aviation Agency (ANAC) and Brazilian Airport Infrastructure Company (INFRAERO) reports from 2015 to 2021. The friction coefficients were measured periodically and categorized by runway thirds and transverse distances from the centerline. This research included seven runways across five airports, with records of aircraft movements and friction coefficients measurements. The analysis focused on identifying patterns that indicate correlations between air traffic and runway surface wear. The friction coefficient data were paired with landing operation data, enabling the calculation of correlations across different runway segments. The results revealed inverse correlations, with increased landing operations correlating with reduced friction coefficients. Some variations in results can be attributed to the differing quantities of each aircraft model on the airport runways. These findings underscore the importance of continuous monitoring and preventive maintenance to ensure the safety and efficiency of airport operations. By providing a data-driven approach, this study offers valuable perceptions for airport infrastructure management and maintenance.

Keywords: Friction Coefficient, Aircraft Movements, Airport Maintenance, Skid Resistance, Surface Wear.

ACKNOWLEGDEMENTS

The authors would like to thank the Brazilian National Civil Aviation Agency (ANAC) and the Brazilian Airport Infrastructure Company (INFRAERO) for providing the essential data and reports that made this research possible.

.

1 INTRODUCTION

The efficient and safe landing of aircraft is a critical aspect of airport operations. One key factor that influences this process is the friction coefficient of the airport runway. (Biancardo et al., 2020). Those aspects, link friction coefficient, are also likely to influence landing operations, as they can impact the overall efficiency and safety of the airport. Sales et al. (2021), argue that the buildup of rubber, originating from aircraft tires, impairs adherence by filling the macrotexture and reducing the friction coefficient of the surface. Therefore, it is necessary to perform periodic rubber removal procedures on the surface to restore adherence conditions. (Young & Wells, 2014)

To ensure safety during aircraft operations, it is necessary to maintain the pavement surface in acceptable operational conditions to prevent accidents or incidents (Oliveira, 2016). Airport operators must maintain the runway in a condition that safely guarantees: (i) skid resistance, (ii) the directional control of the airplanes, and (iii) the integrity of the aeronautical equipment (ANAC, 2019). One of the main aspects to be assessed in this context is tire-pavement grip, which involves monitoring the friction coefficient, the macrotexture, and the rubber accumulation from the airplane tires (Quariguasi et al., 2021). Since these parameters influence safety in touchdown zones, horizontal curves and on wet pavements (Mattos, 2009).

Since, the aircraft taxiing on runways relies on the skid resistance generated by the tires and the runway surface, which enables the aircraft to safely accelerate, turn, taxi, and eventually stop the aircraft from moving (Niu et al., 2020). Therefore, ANAC (2021) establishes that the friction coefficient should be monitored according to the average number of daily landings of fixed-wing aircraft with a jet engine. Quariguasi (2020) reinforce that the greater the number of operations at the aerodrome, the more measurements must be taken to ensure safe operating conditions.

Although the tire-runway friction directly contributes to aircraft stability on land, some of the traditional methods used to measure the texture present some limitations due to their accuracy, efficiency and reliability (Sousa, 2021; Yu et al., 2020). Since the friction characteristics of runways change over time and are related to the frequency of aircraft, climatic and environmental conditions, the presence of contaminants, especially rubber from aircraft (Oliveira, 2008). It is therefore necessary to provide them adequately to guarantee the minimum operational safety conditions for aircraft.

Given this context, the general objective of this study is to analyze the correlation between the temporal variation of runway friction coefficients and the number of landings that occurred during the same period at Brazilian aerodromes. The analysis was conducted across different thirds of the runway and at various transverse distances from the runway centerline. The study can lead to pattern detection that might indicate a connection between air traffic and runway surface degradation.

2 LITERATURE REVIEW

ANAC (2012) states the maintenance level and the minimum friction coefficient according to the equipment used for measurement, as other parameters for working with those devices. It also specifies the maintenance frequency based on the number of landings of jet-engine aircraft. However, this criterion does not consider other factors, such as the model and characteristics of the aircraft and the specifics of the landing operation, which can directly influence the degradation of the runway's friction coefficient.

The maintenance level friction coefficient is the value below which actions must be initiated to restore the friction coefficient to a level equal to or greater than that indicated in the resolution. The minimum friction level is defined as the value below which the runway, when wet, may compromise the braking performance of aircraft on the ground (ANAC, 2012). Techniques and models for predicting friction degradation, in addition to traditional methods, are important tools to aid airport

operators to better manage assets and financial resources for maintenance. Feitosa et al. (2018), for example, studied the influence of the grooving on the friction performance of a runway even on rubber removal events.

The historical of improving skid resistance prediction models for better decision-making is recently discussed (Biancardo et al., 2020; De Luca & Dell'Acqua, 2014; Putov et al., 2016), part of them uses several variables as input such as the volume of air traffic, the number of landings, and the characteristics of the pavement, as well as environmental factors. Studies correlating friction coefficient and landing operations showed that runway surface conditions can significantly influence aircraft braking performance and landing operations efficiency. Variations in the friction coefficient can impact landing operations, requiring airport operators to closely monitor runway surface conditions and implement appropriate maintenance strategies.

Other research efforts are focused on developing new measurement equipment that is more precise, efficient, and cost-effective (Ueckermann et al., 2015; Zuniga-Garcia & Prozzi, 2019). Advancements in sensor technology and data processing have paved the way for innovative friction measurement devices that offer higher accuracy and reliability. These new tools are designed to provide real-time data, reducing the time required for runway inspections and minimizing disruptions to airport operations. Additionally, the development of more affordable measurement solutions makes it feasible for a wider range of airports, including those with limited budgets, to implement regular and thorough runway friction assessments, like the one developed by Niu et al. (2020).

Niu et al. (2021) reviewed techniques for measuring runway friction characteristics to enhance safety during aircraft landings. The authors analyzed the pros and cons of conventional methods and tribo-system-based methods, suggesting future research directions to develop new measurement techniques considering the combined effects of tires, runway, contaminants, and atmospheric conditions. Qian & Wang (2023) aimed to predict the friction coefficient between aircraft tires and wet grooved pavement, evaluating braking distance on wet runways. Their comprehensive tire-pavement-water interaction model considers variables such as tire wear, water film thickness, speed, and tread depth loss.

Wang et al. (2008) developed a model to eliminate errors caused by high-speed measurement processes, considering factors like contamination and slipcover characteristics, tire types, pavement conditions, and weather characteristics. Various studies have explored alternative techniques for determining the friction coefficient and identifying rubberized areas on runways, such as aerial imaging (Aquino et al., 2022; Mota & Oliveira, 2024). This non-intrusive approach enhances the ability to detect wear and rubber deposits, aiding in timely maintenance actions and supporting the development of predictive models for friction degradation.

Neural networks and artificial intelligence (AI) techniques show promise in assisting airport operators with decision-making processes (Quariguasi, 2020; Šabanovič et al., 2020). AI models can analyze large datasets, identify patterns, and predict future runway conditions based on historical data and real-time inputs, helping operators anticipate maintenance needs and optimize resource allocation. Watanabe et al. (2023) highlight how changes in road surface conditions affect runway friction characteristics, with varying influences depending on pavement conditions. Pasindu (2020) emphasizes the need to analyze environmental factors like cooling air speed, humidity, and soaking time in understanding friction coefficient changes in friction materials.

3 METHODOLOGY

For this research, we focused on analyzing the relationship between friction coefficient variation and the number of landings at selected airports and runways in Brazil. The friction coefficient data were collected from ANAC reports, from 2015 to 2021 (ANAC, 2019). The primary sources included monthly aircraft movement reports provided by Brazilian Airport Infrastructure Company – INFRAERO (2024), and detailing landing operations and aircraft types for brazilian aerodromes provided by ANAC (2024).

The runway friction coefficients dataset was then synchronized with the corresponding landing operation data to analyze temporal changes in runway friction in relation to aircraft movements. For this paper seven different runways were object of study, from five different airports at different regions of the country. The measurement dates as the runway extension, pavement coating and runway direction are listed on the Table 1.

Table 1: List and characteristics of runways used on the study

RWY	*Total Length (m)*	*Friction Measurements Campaings*	*Region*	*Period of Measurements*	*Landing Operations on the Period*
01	2,400	15	Northeast	07/2015 - 10/2017	62,905
02	1,600	32	Southeast	07/2015 - 09/2019	492,856
03	3,000	12	Central-West	03/2019 - 11/2021	61,335
04	2,900	12	Central-West	03/2019 - 11/2021	81,115
05	2,600	46	North	08/2015 - 12/2021	110,277
06	1,600	6	North	08/2015 - 05/2020	10,375
07	1,000	12	Southeast	11/2015 - 10/2019	214,025

To estimate the total number of landing operations between each friction coefficient measurement interval, a daily mean was estimated using INFRAERO data, when ANAC data were unavailable on that period. Some of friction data were discarded because landing operation data were not available from the exploited sources.

Considering the measurement variation on each runway portion, a mean value of each third of the runway were determined for each measurement campaign. So, on the middle of the runway is located the 2nd third and, on each runway threshold, were located the 1st and 3rd third. The mean value of the friction coefficient was estimated also differing the transversal distance from the runway longitudinal centerline as regarded on ANAC (2021), 3m and 6m on the left side of the runway (represented by negative values -3m and -6m) and 3m and 6m from the right side of the runway (represented by the positive values 3m and 6m). Being regional airports, the friction coefficient measurements for runways 02, 06, and 07 were carried out only at a 3m transverse distance on each side of the runway centerline.

The friction coefficient data were organized by airport, runway, measurement date, transverse distance, and runway third. Variations in the friction coefficient were calculated between consecutive measurement dates to assess temporal changes.

The weighted average friction coefficient (μ) was determined using the Equation (1):

$$\mu_{weighted} = \frac{\sum_{i=1}^{n} \omega_i \mu_i}{\sum_{i=1}^{n} \omega_i} \quad (1)$$

Where:

- $\mu_{weighted}$ is the weighted average friction coefficient;
- μ_i is the friction coefficient measured at the i-th point;
- ω_i is the weight associated with the i-th measurement, which in this context is typically the length of the segment over which μ_i is measured;
- n is the total number of measurements within the segment;

The landing data were available in monthly grouped data in CSV files, each one containing detailed records of aircraft movements, including airport codes, aircraft types, and the number of landings. The data were filtered to include only landing operations from those airports used on the research. The data were then aggregated by time the same interval between measurements showed on the csv friction file. The data processing involved several steps to ensure accuracy and consistency. Inconsistencies and missing values in the landing data were addressed by specifying appropriate data types during import. The friction coefficient data and landing data were integrated based on matching airports, runways, and measurement periods.

The integrated dataset allowed for the calculation of correlations between friction coefficient variations and landing counts. The correlation analysis aimed to identify relationships between the temporal variations in runway friction coefficients and the number of landings. The analysis was performed across different runway segments (thirds) and transverse distances to capture localized effects of runway wear.

The friction coefficient data were grouped by transverse distance from the centerline. Pearson correlation coefficients were calculated between the friction coefficient variations and the number of landings for each transverse distance. The data were further grouped by runway thirds (1st, 2nd and 3rd). Correlation coefficients were computed for each runway third to determine which segments exhibited stronger relationships with landing counts. The data analysis was conducted using Python, leveraging libraries such as Pandas for data manipulation (cleaning, integration, and aggregation), NumPy for numerical operations (including correlation coefficients), and Matplotlib for data visualization (bar charts and time-series plots).

4 RESULTS AND DISCUSSION

Correlation matrices of the Pearson coefficients were constructed for each studied airport and runway, enabling a detailed analysis of the relationships between friction and landings on each third and transversal distance of runway center. These matrices facilitated the identification of patterns and trends within the data. The Figure 1 presents those matrices and a color scale it presented to compare the coefficients values.

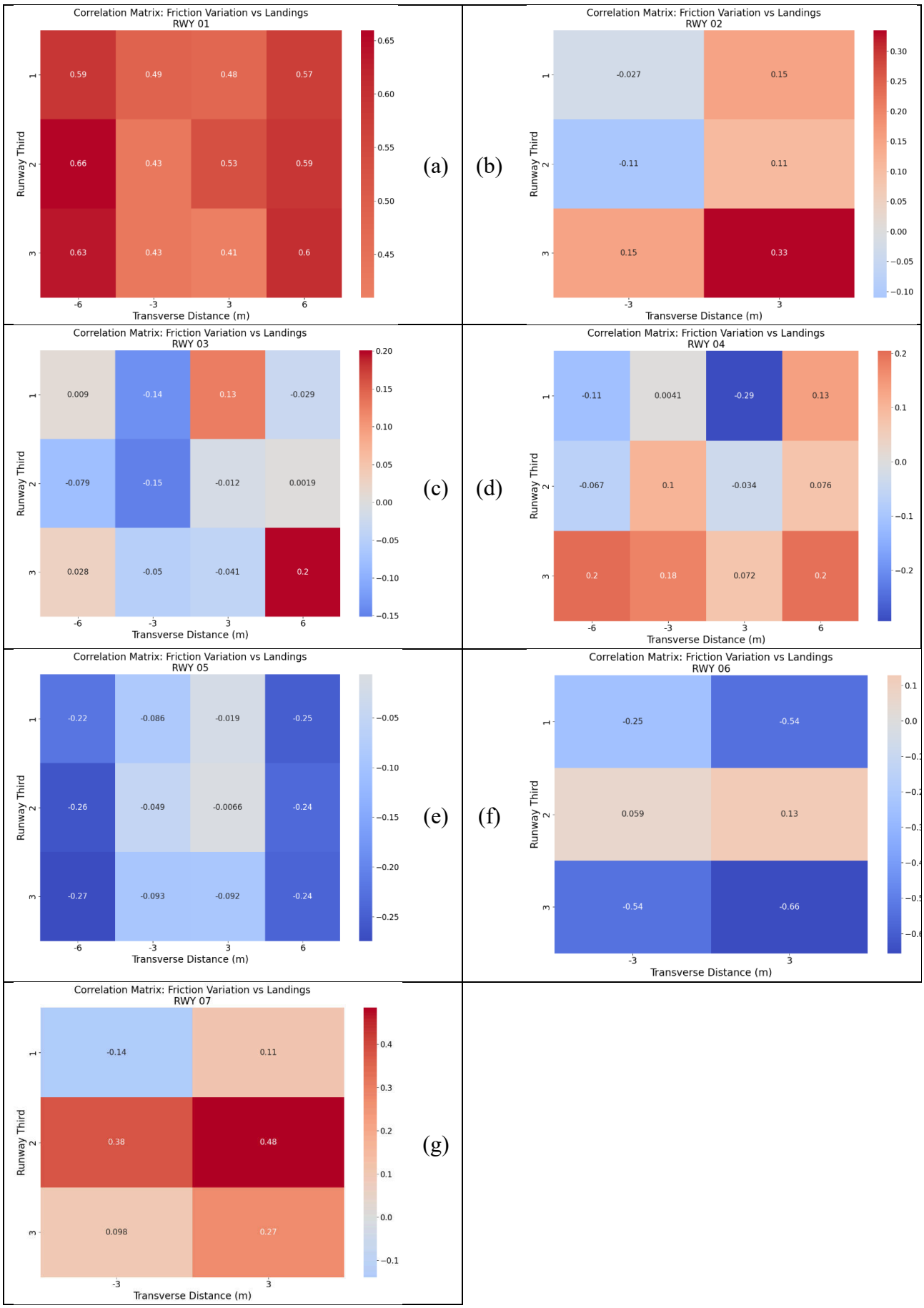


Figure 1 – Correlation matrices between Friction Coefficient Variation and Number of Landings considering transverse distance and runway thirds of RWY 01 (a), RWY 02 (b), RWY 03 (c), RWY 04 (d), RWY 05 (e), RWY 06 (f) and RWY 07 (g).

The initial hypothesis is that there is an inverse correlation, given that the increase in landing operations influences the reduction of friction and consequently also reduces the runway's friction coefficient. The analysis showed partial correlations between the variation in runway friction coefficients and the number of landings across some segments of the runways. Overall, the middle and final thirds of the runways exhibited more pronounced correlations, particularly in measurements taken 3 and 6 meters away from the centerline. These results are consistent with the expectation that heavy air traffic and runway surface wear are interrelated.

The greatest average correlation through the time (Figure 1) occurs on the transverse distance of -6m and 6m, especially on RWY 05 (Figure 1-e), with a Pearson Coefficient of -0,25. This can be better observed on the time graphic presented on the Figure 2.

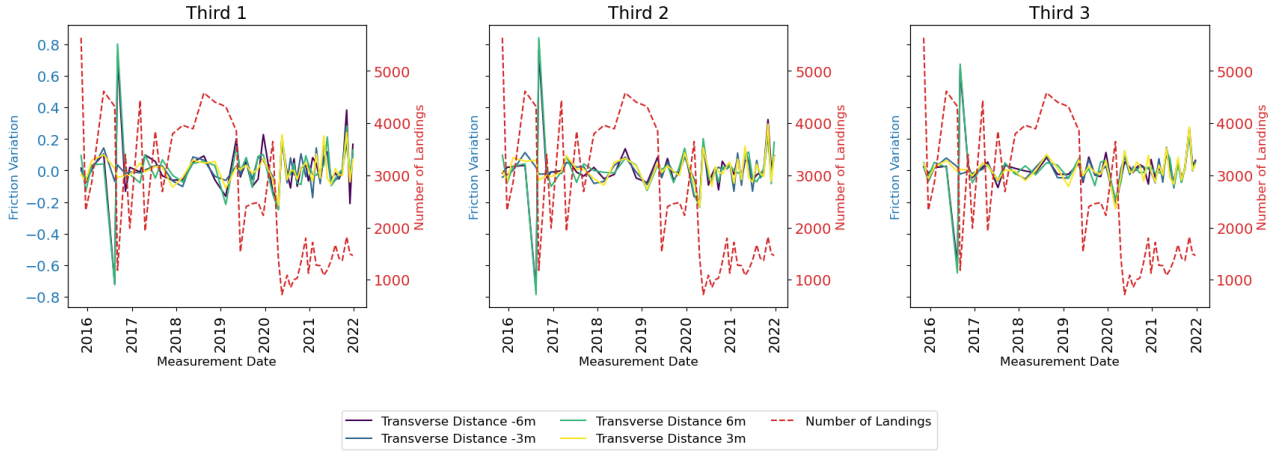


Figure 2 – Temporal analysis of Friction Coefficient Variation and Number of Landings on the three thirds of RWY 05

As can be seen on the RWY 06 (Figure 1-f) the Pearson coefficient reached -0,66 on the last third of the runway, and it can be better observed on the time graphics presented on the Figure 3.

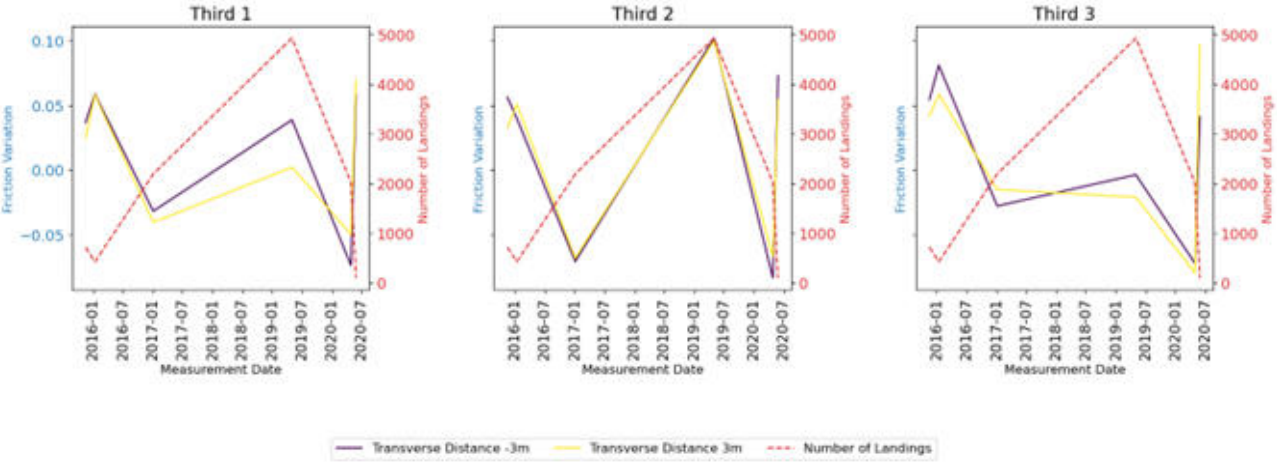


Figure 3 – Temporal analysis of Friction Coefficient Variation and Number of Landings on the three thirds of RWY 01

The results also indicated that wear is particularly pronounced in the middle thirds of the runways. The central area of the runways is a critical zone where the transition between takeoff and landing occurs, which may explain the higher observed correlation in this segment. The final third of the runway, used for deceleration and taxiing after landing, also showed significant correlations, though slightly lower than the middle third.

Some of the low correlation coefficient results on some runways can be explained by pavement rehabilitation or other coating interventions as rubber removal. Also, due to COVID-19 pandemic, during great part of the year 2020 and part of the year 2021 the landing operations on worldwide

airports experienced a severe reduction and, for a long time, operated predominantly with smaller aircraft than usual, as can be seen on the Figure 4 that presents the comparison of top 5 aircraft models that landed on RWY 01. These data may have worked as outliers and interfered with the construction of the correlation between landing and friction coefficient data.

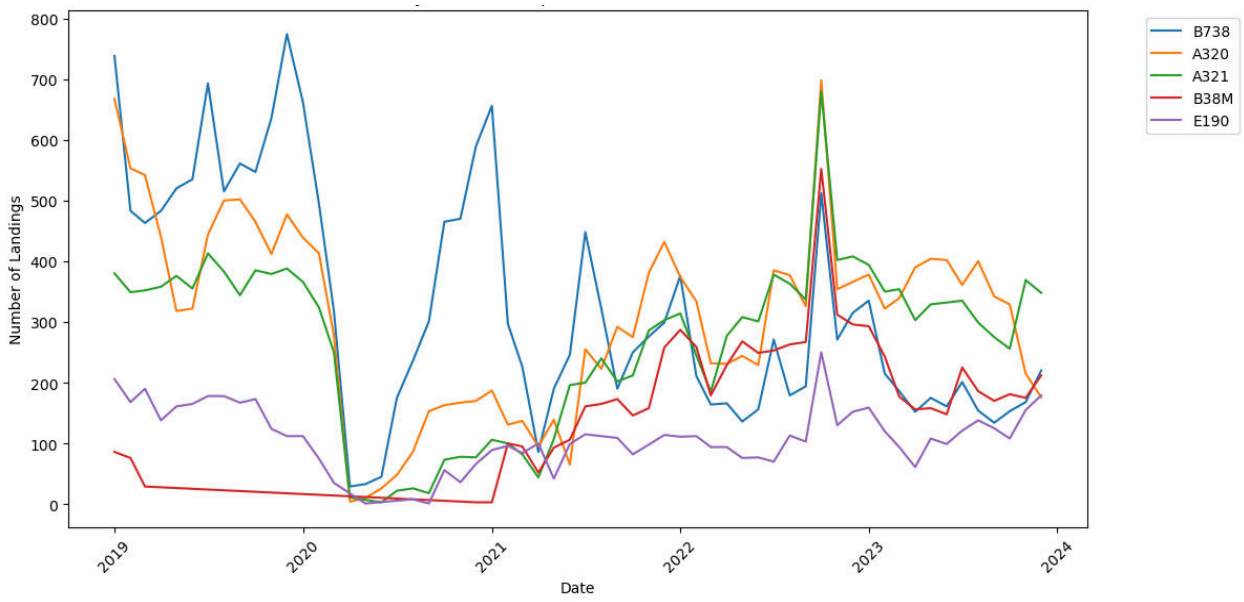


Figure 4 – Temporal analysis of aircraft landing operations of RWY 01 from 2019 to 2024

During landing, the aircraft's weight and tire forces are primarily concentrated in areas farther from the centerline, leading to significant wear in these regions. The varying distances and configurations of each aircraft's landing gear can explain the different correlations observed in measurements taken 3 and 6 meters from the centerline. For instance, RWY 05 and RWY 06 had historical landing proportions of 25% and 22%, respectively, for aircraft with less than a 4m distance between the tandem tires of the main landing gear. In contrast, the other runways had a maximum of 4% for such aircraft models, as shown in Table 2 compiled from ANAC (2024).

Table 2: Distribution of Aircraft Landings by Main Landing Gear Tandem Spacing Classification

Wheelbase distance of the Main Landing Gear	*RWY 01*	*RWY 02*	*RWY 03*	*RWY 04*	*RWY 05*	*RWY 06*	*RWY 07*
Up to 4m	4%	4%	2%	0%	25%	22%	4%
From 4m to 7,5m	68%	95%	77%	84%	59%	40%	96%
Above 7,5m	18%	2%	14%	16%	16%	0%	0%
N/A (Helicopters)	10%	0%	7%	0%	0%	39%	0%

Environmental factors such as temperature variations, rain, and other weather elements significantly contribute to runway surface degradation, as discussed by Pasindu (2020) and Watanabe et al. (2023). These elements can serve as model variables to enhance the prediction of runway friction coefficients. The frequency and quality of maintenance and repairs also directly influence the variation in friction coefficients over time. It is expected that runways with more frequent and high-quality maintenance methods exhibit smaller variations in friction coefficient, even under high landing volumes.

The methodology applied and results obtained emphasize the importance of an integrated, data-driven approach to effective airport infrastructure management. The strong correlation between air traffic and runway wear underscores the necessity for continuous monitoring and preventive maintenance, thereby ensuring the safety and efficiency of airport operations.

5 CONCLUSIONS

In this research, the relationship between friction coefficient variation and the frequency of landings at selected Brazilian airports and runways was examined. Runway friction coefficients were measured periodically and categorized by runway thirds and transverse distances from the centerline. Seven different runways from five airports were studied, their friction data synchronized with landing operation data, enabling analysis of temporal changes in runway friction relative to aircraft movements.

Results indicate inverse correlations between runway friction coefficient variations and the number of landings across some runways. Middle and final thirds of the runways showed more pronounced correlations, especially at 6m from the centerline. This aligns with expectations that heavy air traffic and decrease of runway surface friction are interrelated.

The results obtained in this study have important implications for airport infrastructure management. The identified correlations provide a solid foundation for implementing preventive maintenance programs aimed at mitigating runway wear and extending its lifespan. By focusing on the areas identified as critical, such as the middle and final thirds of the runways and the lateral regions, airport authorities can optimize resources and ensure greater operational safety. The findings highlight the importance of continuous monitoring and preventive maintenance, ensuring the safety and efficiency of airport operations. Implementing data-driven approaches can optimize infrastructure management, extend runway lifespan, and enhance operational planning.

6 REFERENCES

ANAC. (2019). *Dados abertos — Agência Nacional de Aviação Civil ANAC*. https://www.anac.gov.br/acesso-a-informacao/dados-abertos

ANAC. (2021). *RBAC nº 153 Aeródromos - Operação, Manutenção e Resposta à emergência*.

ANAC. (2024, setembro 20). *Dados de Movimentação Aeroportuária*. Acesso à Informação - Ministério de Portos e Aeroportos. https://www.gov.br/anac/pt-br/acesso-a-informacao/dados-abertos/areas-de-atuacao/operador-aeroportuario/dados-de-movimentacao-aeroportuaria

Aquino, T. S. de A., Oliveira, F. H. L. de, & Mota, G. (2022). Caracterização do Acúmulo de Borracha por Meio de Processamento de Imagens e por Análise das Operações de Pousos e Decolagens. *SITRAER 2022, Air Transportation Symposium*.

Biancardo, S. A., Abbondati, F., Russo, F., Veropalumbo, R., & Dell'Acqua, G. (2020). A broad-based decision-making procedure for runway friction decay analysis in maintenance operations. *Sustainability (Switzerland)*, *12*(9). https://doi.org/10.3390/SU12093516

De Luca, M., & Dell'Acqua, G. (2014). Runway surface friction characteristics assessment for Lamezia Terme airfield pavement management system. *Journal of Air Transport Management*, *34*, 1–5. https://doi.org/10.1016/j.jairtraman.2013.06.015

Feitosa, L. A., Neto, P. de S. L., Santos, F. H. D. dos, & Oliveira, F. H. L. de. (2018). *Análise exploratória do desempenho do coeficiente de atrito em pavimento aeroportuário*. *October*.

INFRAERO. (2024). *Estatísticas*. Portal Transparência Infraero. https://transparencia.infraero.gov.br/estatisticas/

Mattos, J. R. G. (2009). *Avaliação da aderência pneu-pavimento e tendências de desempenho para a rodovia BR-290/RS*. 139.

Mota, G., & Oliveira, F. H. (2024). *K-means segmentation on color-scale runways images to correlate with coefficient of friction data*.

Niu, Y., Jiang, X., Meng, F., Wang, R., Ju, G., Zhang, S., & Meng, Z. (2021). Techniques and Methods for Runway Friction Measurement: A Review of State of the Art. *IEEE Transactions on Instrumentation and Measurement*, *70*(June 2021). https://doi.org/10.1109/TIM.2021.3092062

Niu, Y., Zhang, S., Tian, G., Zhu, H., & Zhou, W. (2020). Estimation for Runway Friction Coefficient Based on Multi-Sensor Information Fusion and Model Correlation. *Sensors*, *20*(3886).

Oliveira, F. H. L. de. (2008). Proposição de estratégias de manutenção de pavimentos aeroportuários baseadas na macrotextura e no atrito: estudo de caso do Aeroporto Internacional de Fortaleza. *VII SITRAER*, 178–182.

Oliveira, F. H. L. De. (2016). *Desenvolvimento de um modelo de gerenciamento de pavimentos aeroportuários como apoio à tomada de decisão sobre estratégias de manutenção e reabilitação*. Universidade Federal do Ceará.

Pasindu, H. R. (2020). Analytical evaluation of impact of groove deterioration on runway frictional performance. *Transportation Research Procedia*, *48*, 3814–3823. https://doi.org/10.1016/j.trpro.2020.08.038

Putov, V. V., Putov, A. V., Stockaia, A. D., Sheludko, V. N., & Ignatiev, K. V. (2016). The method and technical facilities for measurement of airfield friction coefficient and it's correlation with the characteristics of aircraft braking during landing. *13th International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE)*. https://doi.org/10.1109/APEIE.2016.7806994

Qian, J., & Wang, H. (2023). Analysis of skid resistance and braking distance of aircraft tire landing on grooved runway pavement. *International Journal of Pavement Engineering*, *24*(2). https://doi.org/10.1080/10298436.2022.2101054

Quariguasi, J. B. F. (2020). *Previsão do Coeficiente de Atrito em Pista de Pouso e Decolagem Utilizando Redes Neurais Artificiais*. Universidade Federal do Ceará.

Quariguasi, J. B. F., Oliveira, F. H. L. de, & Reis, S. D. S. e. (2021). Modelo de previsão do coeficiente de atrito para pista de pouso e decolagem com uso de redes neurais artificiais. *TRANSPORTES*, *29*(2), 2401–2401. https://doi.org/10.14295/TRANSPORTES.V29I2.2401

ANAC. (2012). *RESOLUÇÃO Nº 236, DE 5 DE JUNHO DE 2012* (236).

Šabanovič, E., Žuraulis, V., Prentkovskis, O., & Skrickij, V. (2020). Identification of road-surface type using deep neural networks for friction coefficient estimation. *Sensors (Switzerland)*, *20*(3). https://doi.org/10.3390/s20030612

Sales, R. de S., Oliveira, F. H. L. de, & Prado, L. de A. (2021). Performance of tire-asphalt pavement adherence according to rubber removal on runways. *International Journal of Pavement Engineering*, *23*(10), 3566–3576. https://doi.org/10.1080/10298436.2021.1907577

Sousa, J. M. P. de. (2021). *Estudo do desempenho de um protótipo de medição de atrito em pavimentos rodoviários*. Universidade do Minho.

Ueckermann, A., Wang, D., Oeser, M., & Steinauer, B. (2015). A contribution to non-contact skid resistance measurement. *International Journal of Pavement Engineering*, *16*(7), 646–659. https://doi.org/10.1080/10298436.2014.943216

Wang, L. W., Yu, Z. J., Zhang, L., Gao, J., & Song, J. (2008). Study on the Key Technology of Airport Runway Frictional Coefficient Measurement. *Key Engineering Materials*, *381–382*, 229–232. https://doi.org/10.4028/www.scientific.net/KEM.381-382.229

Watanabe, A., Kageyama, I., Kuriyagawa, Y., Haraguchi, T., Kaneko, T., & Nishio, M. (2023). Study on the Influence of Environmental Conditions on Road Friction Characteristics. *Lubricants*, *11*(7), 277. https://doi.org/10.3390/lubricants11070277

Young, S. B., & Wells, A. T. (2014). *Aeroportos - Planejamento e Gestão*. Bookman.

Yu, M., You, Z., Wu, G., Kong, L., Liu, C., & Gao, J. (2020). Measurement and modeling of skid resistance of asphalt pavement: A review. *Construction and Building Materials*, *260*, 119878. https://doi.org/10.1016/j.conbuildmat.2020.119878

Zuniga-Garcia, N., & Prozzi, J. A. (2019). High-Definition Field Texture Measurements for Predicting Pavement Friction. *Transportation Research Record*, *2673*(1), 246–260. https://doi.org/10.1177/0361198118821598