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# Flight Test Analysis and Flight Manual Modelling of the Rolling and Braking Resistance over Unpaved Runways

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## Abstract

The performance of an aircraft, especially military platforms, over unpaved runways is of great importance and strategic for the success of any air force operations during war and peace scenarios. This work has the objective of showing flight test results analysis of take-off and braking performance over unpaved runways with and without vegetation. The physical phenomenon behind the increase of the rolling resistance when performing a take-off over unpaved runway is explained by introducing the concepts behind the compactation drag of the aircraft tyres when compressing the soil, besides the bulldozing effect and its correlation to the soil mechanical properties. The existing models for unpaved rolling resistance modelling, derived based on soil mechanics concepts, the Bekker and more recently Grahm models, will be presented and their limitations and difficulties on predicting aircraft behaviour will be outlined. The California Bearing Ratio (CBR) and the Cone Index (CI) are introduced as the most common methods for assessing the unpaved runway state, and these indexes will be used to correlate the aircraft behaviour with the soil characteristics. The aircraft rolling and braking resistance coefficients over soil with and without vegetation are showed as a function of the measured CBR along the runway and the vegetation effect will be outlined due to its distinct results when compared with the resistance over soils without vegetation. Other effects of parameters such as aircraft weight, tyre pressure and runway rutting are calculated and their impacts are measured. To conclude, a method based on dimensional analysis, using the Buckingham theorem is proposed as a way to generalize the results and develop a methodology to aid tests planning and results prediction.

## 1. Introduction

The rolling and braking performance on paved runway is well established inside the aeronautical industry and published regulations and models are already available and constantly used during aircraft performance certification. In contrast, the behaviour of aircraft performance on unpaved runways is complex due to the soil and tyre interactions which are still under investigation.

The operations over unpaved airfields are usually, but not limited, encountered in military air-lifters. This special functionality of these military aircrafts are aimed as an operational advantage as it allows for take-off and landing over non paved runways inside the operational theatre. This is considered as a major advantage due to allowing for strategic infiltration and extraction from the war scenario.

There are published works and models for the unpaved drag characteristics specially useful for agricultural and military road vehicles, but these methods are only validated for low speed vehicles, higher speeds usually encountered in take-off and landings are not covered therefore the methodology is not valid for aircraft operations.

The current civil regulation(1) regarding unpaved runways take-off performance and landing states that the information inside the Aircraft Flight Manual must be based on extensive flight test which covers and correlates the aircraft rolling and braking performance with different soil mechanical properties and characteristics. Therefore a methodology to analyse flight test and expand and generalize these results to publish the performance information is presented.

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This work proposes a simple methodology to correlate the rolling and braking coefficient over unpaved runways with the soil mechanical properties, measured by the California Bearing Ration (CBR), the presence of vegetation roots, soil degradation expressed as rutting and aircraft characteristic as its weight and tyre pressure.

## 2. Unpaved Runways

For the unbraked rolling drag acting on take-off run, basically two distinct phenomenon appear on unpaved runways, the first is the soil compression by the aircraft tyres which dissipates energy, increasing ground resistance.

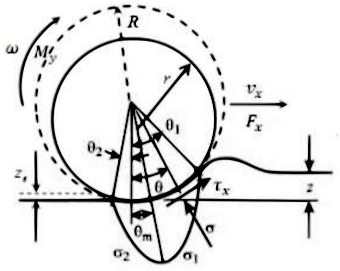

Figure 1: Compression drag [3].

At Fig. 1 the tyre compressing the soil produces the radial and shear stress distributions ($\sigma$, $\tau$) causing a moment acting contrary to the aircraft rolling direction and hence, increasing the rolling resistance.

Besides the compresison drag, there is the bulldozing effect which is the soil resistance due to the aircraft wheel pushing soil layers from the front to the side of the tyres while rolling.

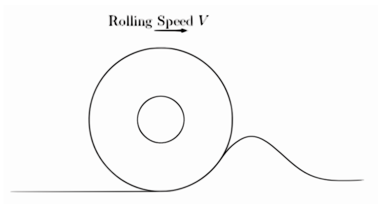


Figure 2: Bulldozing drag [3].

Other challenge on modelling the drag caused by the soil is the multipass effect. The ground when compressed by the wheels will react similar to a stress strain relationship as in metals. The soil will be under elastic and plastic deformation and the following set of wheels will face different level of soil compactation; changing the soil compression drag and bulldozing effect.

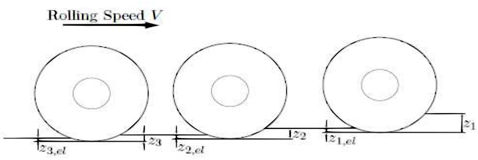


Figure 3: Multipass effect [3].

### 2.1 Soil Characterization

The soil mechanical properties play an important role in the tyre-soil interaction and consequent rolling drag. The soil shear strength characterized by the normal stress applied to the ground $\sigma$, internal friction angle

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$\phi$ and soil cohesion $c$ are responsible for the additional drag caused by the aircraft rolling over unpaved runways.

$$\tau = c + \sigma \cdot tg(\phi) \tag{1}$$

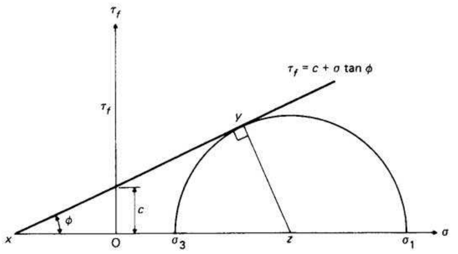


Figure 4: Soil Shear Strenght[(3)].

In military aircraft operations, a typical method used to characterize the runway is the soil bearing strength. The most common method used is the California Bearing Ratio (CBR). The advantage of this procedure is that it enables an in-situ determination of the runway bearing strength.

The CBR ratio is the relation of the actual soil strength to that of a crushed limestone. The test consists of a penetration probe driven into the soil at constant rate and a comparison between the penetration stress with the reference value for the crushed limestone defines the CBR value.

Figure 5: CBR Evaluation for Fokker F28 Certification Tests[(3)].

Other methodology developed by the US Army is the Cone Index (CI), the test consists of a standard cone probe used to penetrate into the soil until a depth of 2 ft. The index is related to the pressure necessary to keep the cone movement into the ground. An approximate linear relationship exists between the cone index and CBR.

$$CI = 40 \cdot CBR \tag{2}$$

The Cone Index, hence the CBR, is related to the soil mechanical properties cohesion $c$ and friction angle $\phi$. Higher values of CI/CBR are correlated to high soil mechanical properties which are therefore related to the soil resistance to movement, which causes the additional rolling drag.

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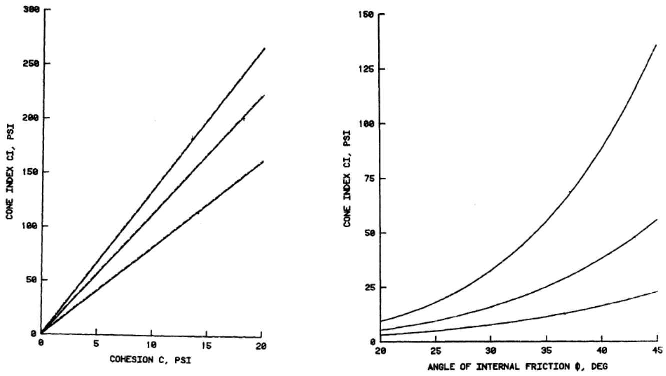


(a) Relation between CI and soil Cohesion [4]

(b) Correlation between CI and Soil Friction Angle [4]

Figure 6: Correlation between CI and Soil Properties [4]

At Fig. 6a and 6b, each curve represents a soil with different strength and all of them show an increase at the Cone Index and CBR related to the soil cohesion and friction angle.

### 2.2 Vegetation Effect

The roots present below unpaved runway covered with vegetation alters soil characteristics by increasing the soil strength. There is a significant effect on soil cohesion and a smaller change in soil friction angle [2]. The complexity of the vegetation effect relies on being dependent on the roots size and geometry and the increase in soil strength is dependent on these two parameters.

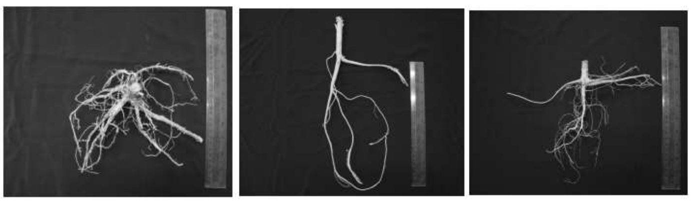

Figure 7: Roots encountered on unpaved runway [2].

The three different types of roots shown in Fig. 7 increase the soil strength and consequently the CBR ratio, therefore the rolling resistance on unpaved runway with vegetation is expected to decrease due to this higher CBR producing lower compression drag.

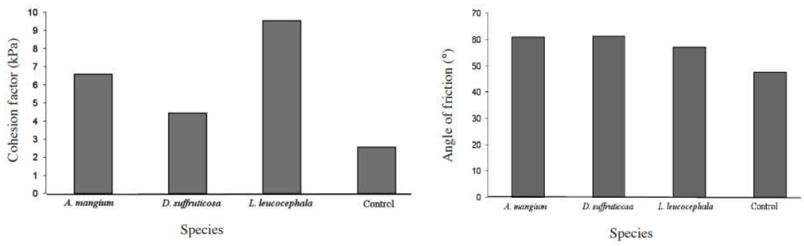


Figure 8: Effect of Vegetation on Soil Strength [2].

## 3. Rolling Resistance Model

### 3.1 Rolling Drag

The rolling drag behaviour over unpaved runway is separated between soil compactation drag and the bull-dozing effect. The resistance due to soil compactation is divided in three distinct regions where different

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phenomenon are predominant. At low speeds, the tyre sinkage is high and the magnitude of the drag is proportional to the tyre area in contact with the ground, it is characterized by a viscous effect. As speed increases with acceleration, the tyre lift reduces the contact area with the soil and drag is reduced, but at the same time, the forward speed moves the peak contact pressure towards the leading edge of the tyre footprint area, increasing the compression drag. At a critical speed, this effect becomes predominant over the viscous drag and the rolling resistance starts to increase with speed causing a minimum drag region. The drag is increased until the local lift on the tyre is equal to the vertical load when a phenomenon called soil-planing, similar to hydroplaning occurs and the drag ratio begins to decrease with speed, therefore a region of maximum drag just before soil-planning is formed.

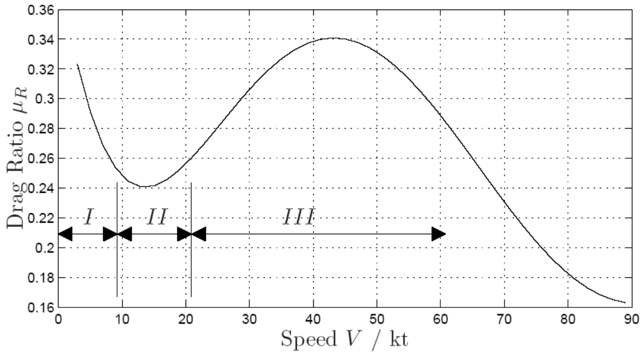


Figure 9: Drag Ratio with speed over unpaved runways [3].

The rolling compactation drag value in Fig. 9 is influenced by the soil bearing capacity represented by the runway CBR value. For low CBR the tyre sinkage is higher and also the drag ratio. For higher CBR the tyre sinks less on the ground and the drag behaviour becomes closer to the paved runway characteristics.

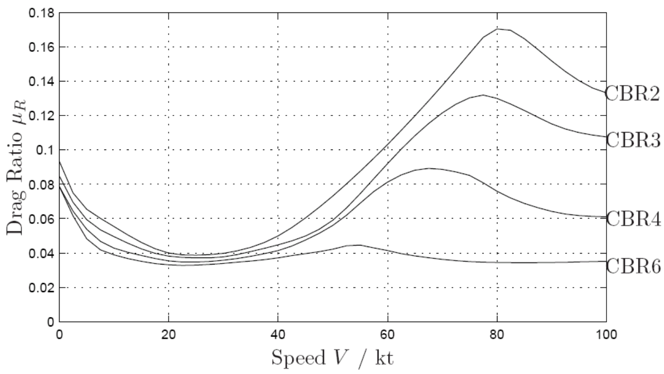


Figure 10: Drag Ratio with CBR effect [3].

Besides the CBR effect, other parameters may alter the drag ratio function for unpaved rolling resistance. Since the rolling drag is closely related to the tyre sinkage, every aircraft parameter affecting it, will alter the rolling resistance:

- Tyres diameter and width.
- Tyres pressure.
- Aircraft weight over tyre axle.
- Tyres loaded deflection.

The items listed above are related to the footprint area and pressure exerted on the ground producing the tyre sinkage.

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### 3.2 Tyre-Soil Interaction Models

The first attempt to develop a relationship between vertical load and sinkage ($z$) as a function of soil characteristics is due to the work of Bekker[(3)]. A relationship between pressure and sinkage was established through experimental results.

$$p = k \cdot z^n \tag{3}$$

The values of $k$ and $n$ are soil properties parameters and are linked to the soil mechanical properties cohesion and friction angle. The integration of the pressure distribution ($p$) over contact area defines the vertical and horizontal loads acting on the wheel.

$$\begin{aligned} F_z &= k \cdot B \int_0^{z_0} z^n dx \\ F_x &= k \cdot B \int_0^{z_0} z^n dz \end{aligned} \tag{4}$$

At Eq. 4 the vertical force is the integration of the pressure distribution over the horizontal area ($B \cdot dx$) and the horizontal force is calculated over the vertical area ($B \cdot dz$). The value of $z_0$ is the maximum sinkage value and $B$ is the tyre width. Integrating both equations yield to the expressions for sinkage and horizontal resistance applied on each aircraft tyre according to Bekker theory[(3)].

$$\begin{aligned} z_0 &= [\frac{F_z}{(3-n)\sqrt{2R}Bk}]^{\frac{2}{2n+1}} \\ F_x &= B \cdot k \frac{z_0^{n+1}}{n+1} \\ \text{R} &= \text{Tyre Radius} \end{aligned} \tag{5}$$

The major disadvantage of Eq. 5 is that the Bekker model does not consider wheel speed on the sinkage and drag model therefore is only valid for small speeds and cannot be applied to aircraft rolling during take-off or landing.

To overcome this disadvantage, a more complex model proposed by Grahn[(3)] accounts for the speed dependency by assuming that the pressure over the ground is a function not only of sinkage but also the sinkage rate.

$$\begin{aligned} p &= (k + k_{dyn} \cdot \dot{z}^m) z^n \\ \dot{z} &= 2V\sqrt{\frac{z_0 - z}{2R}} \end{aligned} \tag{6}$$

Similar to the Bekker model, integrating the pressure over the horizontal and vertical areas, a model of the forces can be established as a function of speed.

$$\begin{aligned} z_0 &= [\frac{F_z}{B\sqrt{2R}(k[1-\frac{n}{3}] + k_{dyn}[2V]^m[\frac{1}{m+1} - \frac{n}{3+m}][\frac{z_0}{2R}]^{\frac{m}{2}}}]^{\frac{2}{2n+1}} \\ F_x &= B[\frac{k}{n+1} + k_{dyn}(2V)^m 2(\frac{1}{2+m} - \frac{n}{4+m})(\frac{z_0}{2R})^{\frac{m}{2}}] \cdot z_0^{n+1} \end{aligned} \tag{7}$$

The difficulty on applying Eq. 7 is the necessity to solve it iteratively both equations for the identified soil parameters $k, k_{dyn}, m, n$.

Besides the soil compactation resistance expressed by the Bekker or Grahn models, the bulldozing effect can be estimated based on the soil bearing capacity and its coefficients based on the Terzaghi bearing loading model.

The bulldozing drag is dependent on the tyre sinkage ($z$), the tyre geometry ($B$ and $D$), soil drained cohesion, friction angle and specific weight ($C$, $\phi$, $\gamma$) and the soil bearing coefficients $K_c$ and $K_\gamma$.

$$\begin{aligned} F_b &= \frac{B \cdot sin(\alpha + \phi)}{2 \cdot sin(\alpha) cos(\phi)} \cdot [2 \cdot z \cdot C \cdot K_c + \gamma \cdot z^2 \cdot K_\gamma] \\ \alpha &= acos(1 - \frac{2z}{D}) \end{aligned} \tag{8}$$

The bearing coefficient are mainly functions of the soil friction angle, therefore the bulldozing effect is more predominant in soils with high friction slopes. According to Terzaghi's theory[(5)]:

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$$
\begin{aligned}
K_c &= (N_c - tg(\phi)) \cdot cos(\phi)^2 \\
K_\gamma &= (\frac{2 \cdot N_\gamma}{tg(\phi)} + 1) \cdot cos(\phi)^2 \\
N_c &= cot(\phi) \cdot (N_q - 1) \\
N_q &= \frac{exp[(3/2 \cdot \pi - \phi) \cdot tg(\phi)]}{2 \cdot cos(\pi/4 + \phi/2)^2} \\
N_\gamma &= \frac{1}{2} \cdot (\frac{K_{p\gamma}}{cos(\phi)^2} - 1) \cdot tg(\phi) \\
K_{p\gamma} &= (8\phi^2 - 4\phi + 3.8) \cdot tg(\pi/3 + \phi/2)^2
\end{aligned} \tag{9}
$$

## 4. Flight Test Rolling and Braking Coefficient Identification

The runway performance monitoring is translated into the identification of the rolling and braking coefficient ($\mu$). The methodology for identification is the use of the aircraft dynamic equations with the observation of runway distance $S_x$, ground and true speeds $V_g$ and $V_T$ and acceleration $A_x$.

In this work, the methodology proposed for identification is the use of the Kalman Filter technique. Due to the non linearity of the aircraft equations of motion, the Extended (EKF) or the Unscented Kalman Filter (UKF) shall apply.

### 4.1 State Model

The state estimation model is the aircraft dynamics in the longitudinal axis. The acceleration is calculated using Newton's law in the aircraft $x$ axis and the resistance coefficient ($\mu$) is a pseudo-state inside the filter dynamics.

As control variables, there are the engine thrust in the $x$ and $z$ axis ($T_x, T_z$), the drag and lift in ground effect ($D$, $L$), the runway slope ($\phi$) and the aircraft pitch angle on ground ($\theta$). These variables enter the modelling as known parameters, their identification is not the purpose of the filtering process.

$$
\begin{aligned}
\dot{V_g} &= \frac{T_x - D - m \cdot g \cdot sin(\phi) - (m \cdot g - T_z - L) \cdot \mu}{m} \\
\dot{S_x} &= V_g \\
\dot{\mu} &= 0 \\
\dot{V_w} &= 0 \\
T_x &= T \cdot cos(\epsilon + \theta); T_z = T \cdot sin(\epsilon + \theta) \\
D &= \frac{1}{2}\rho \cdot S \cdot {V_T}^2 \cdot CD; L = \frac{1}{2}\rho \cdot S \cdot {V_T}^2 \cdot CL \\
V_T &= V_g - V_w;
\end{aligned} \tag{10}
$$

The modelling equations in 10 assumes the wind speed $V_w$ is constant throughout the runway. The angle $\epsilon$ is the engine incidence angle and throughout the model, the angle of attack $\alpha$ is considered to be equal to the pitch angle $\theta$.

### 4.2 Observation Model

The instrumentation present in the aircraft aids the observability of the runway dynamics permitting the identification of the rolling coefficient. The GPS system, the anemometric system and load factor accelerometers measurements are used to observe the distance, ground speed, true airspeed and acceleration.

$$
\begin{aligned}
\mathbf{y(1)} &= \mathbf{x(1)} = V_g \\
\mathbf{y(2)} &= \mathbf{x(2)} = S_x \\
\mathbf{y(3)} &= \dot{\mathbf{x}}(1) = A_x \\
\mathbf{y(4)} &= V_g - V_w = V_T
\end{aligned} \tag{11}
$$

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With these set of observations, the ground speed ($V_g$) and longitudinal distance ($S_x$) come from the GPS system, the true airspeed ($V_T$) from the calibrated anemometric probes and the acceleration ($A_x$) from accelerometers installed in the aircraft used together with the inertial and clinometric systems to calculate the acceleration in the aircraft longitudinal axis.

## 5. Runway Resistance Model for AFM Generation

The rolling and braking resistance over unpaved runways were outlined previously, focusing on explaining the soil and tyre interactions producing the compactation and bulldozing resistance which adds to the overall aircraft deceleration forces. A methodology was developed with the use of the Kalman Filter for identification of the rolling and braking $\mu$ using parameters usually measured in flight test campaign. This section focuses on developing a generalized model for unpaved runway resistance characterization for the aircraft flight manual.

### 5.1 Analysis of Parameters

Among every parameter affecting the rolling and braking resistance over unpaved runways, a total of 6 were used to generate a resistance model. The aircraft weight (W), tyre pressure (P), ground speed (V), measured CBR, surface type if with vegetation or not and finally if the runway has ruttings along its surface. The parameters effects were divided between quantitative and qualitative variables, the presence of rutting and vegetation were classified as qualitative while weight, tyre pressure, speed and CBR are quantitative variables which will have its impact analytically measured.

#### 5.1.1 Methodology

The methodology developed for quantifying the effect of these variables are based on a process for reducing flight test identified $\mu$ to a single reference $\mu_{Red}$ for a standard value of speed, weight and tyre pressure.

$$\mu_{Red} = K_V \cdot K_W \cdot K_P \cdot \mu_{FT} \tag{12}$$

The $\mu_{Red}$ in Eq. 13 is the reduced resistance coefficient at reference conditions of speed, pressure and weight and the parameters $K_V$, $K_P$ and $K_W$ are the associated factors applied to the flight test measured $\mu_{FT}$. With the reduced coefficient $\mu_{Red}$ at the reference conditions, the only remaining variable affecting its value is the runway CBR. Therefore, combining every flight test result at the reference condition, a plot is made to correlate CBR value with $\mu_{Red}$.

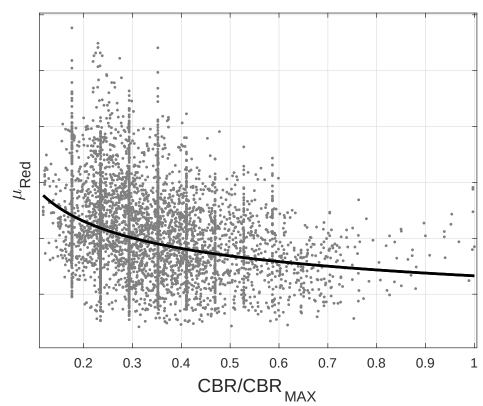


Figure 11: Relation between CBR and $\mu_{Red}$.

A polynomial fit adjusting CBR and $\mu_{Red}$ in Fig. 11 is used calculate the reduced coefficient at any CBR condition. The polynomial model depends on flight test results and if it is a braking or acceleration test.

$$\mu_{Red} = f(CBR) \tag{13}$$

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This polynomial fit along with the speed, weight and tyre pressure factor ($K_V, K_W, K_P$) is used to calculate flight manual take-off and landing data for any set of conditions following the procedure below for each one of the qualitative parameters (presence of vegetation and presence of runway rutting):

1. Given the runway measured $CBR_m$, calculate the reduced resistance coefficient with Eq. 13
2. With the ground speed (V), tyre pressure (P) and aircraft weight (W), to be used in the flight manual data, calculate the coefficients:
$$K_V = f(V), K_W = f(W), K_P = f(P) \tag{14}$$
3. With the speed, pressure and weight factors, calculate the corrected resistance coefficient for these set of inputs ($CBR_m$,V, P, W) as in Eq. 15.
$$\mu = \frac{\mu_{Red}}{K_V \cdot K_W \cdot K_P} \tag{15}$$

The process outlined in the list above has the important hypothesis of considering the effect of speed, weight and tyre pressure as independent among each other, therefore three distinct factors ($K_V, K_W, K_P$) may be applied separately.

The method proposed to predict the three factors are based on a polynomial fit of the identified $\mu_{FT}$ when plotted against each one of the three parameters (speed, weight and pressure).

$$\begin{aligned} \mu_V &= f(V) = \sum_{i=0}^{N_V} A_{V_i} \cdot V^i \\ \mu_W &= f(W) = \sum_{i=0}^{N_W} A_{W_i} \cdot W^i \\ \mu_P &= f(P) = \sum_{i=0}^{N_P} A_{P_i} \cdot P^i \\ K_V = \frac{\mu_{V_{Ref}}}{\mu_V}, K_W &= \frac{\mu_{W_{Ref}}}{\mu_W}, K_P = \frac{\mu_{P_{Ref}}}{\mu_P} \end{aligned} \tag{16}$$

The parameters $A_i$ are the identified polynomial coefficients of degree $N$. This degree depends on the identified correlation between the friction coefficient $\mu_{FT}$ and the measured speed, tyre pressure and weight.

### 5.2 CBR Effect

The effect of the runway CBR is separated between airfields with and without vegetation. For the case of the rolling resistance over soil without vegetation, the results of the AFM model based on flight test measurements, in Fig. 12 show that the measured CBR value has an important effect on the rolling resistance coefficient $\mu$. For these kinds of pavement, the lower CBR will provoke a deeper tyre sinkage on ground which increase the compactation resistance and hence the overall $\mu$.

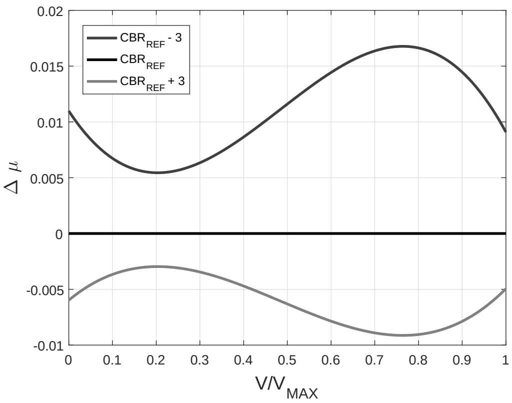


Figure 12: Relation between $\mu$ and ground speed for soil without vegetation.

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For the runways covered with vegetation, the effect of the measured CBR is very small and could be neglected as seen in Fig 13.

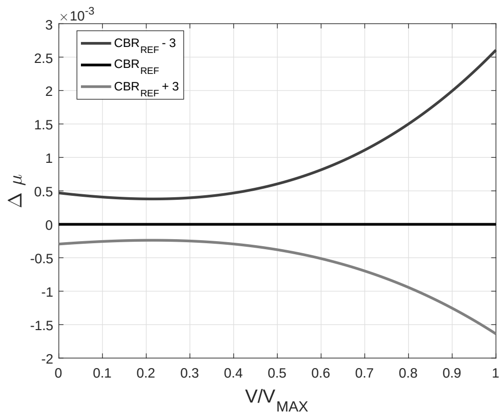


Figure 13: Relation between $\mu$ and ground speed for soil with vegetation.

The overall resistance measured seems independent of the runway CBR for airfields covered with virgin vegetation. A possible explanation for this phenomenon is that the CBR measurement probe uses a penetrometer which breaks the vegetation roots and sinks into the ground measuring its penetration resistance and CBR. This penetrometer does not correlate to the tyre sinkage when accelerating over the runway since the pressure exerted by the tyre will not break the root network as the penetrometer does, resulting in an overall resistance independent of the runway CBR. Besides this, the effect of the vegetation roots are of increasing the soil cohesion and friction angle, these two parameters will affect the distribution of the compactation and bulldozing factors affecting the total rolling resistance. It seems that the presence of roots increases the effect of the bulldozing drag which may explain the distinct behaviour of the increase of $\mu$, postponing the soil planning, at higher speeds when compared to the case without vegetation.

The same procedure was repeated for the test cases with full brakes application at Fig. 14 For both cases, the ground with and without vegetation, the effect of the measured CBR is small on the overall braking resistance coefficient. The effect of the vegetation over the braking resistance is clearer when analysing the bahaviour of the resistance coefficient increase as the aircraft decelerates. The braking coefficient gradient is higher as speed decreases for runways without vegetation, therefore higher average coefficients are expected for these type of runways.

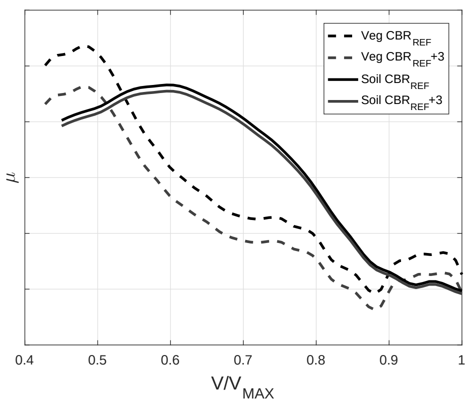


Figure 14: Relation between braked $\mu$ and ground speed.

## 5.3 The Effect of Runway Rutting

The aircraft passing over an unpaved runway provokes rutting along its trajectory. The rutting are paths generated by the sinkage of the aircraft tyre after several passes. These ruts change the overall aircraft

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resistance coefficient and if the runway is not previously prepared in an effort to reduce the rutting, these effect should be considered inside AFM data.

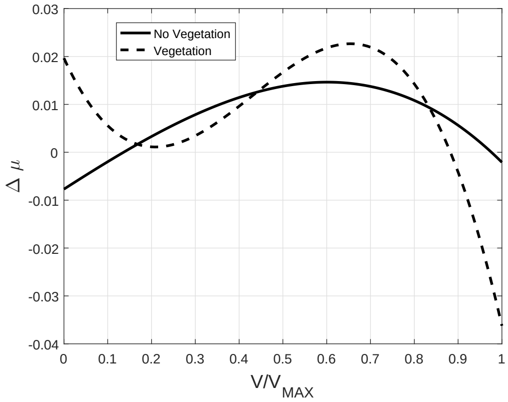


Figure 15: Example of the effect of rutting.

In Fig. 15, the effect of the presence of rutting for the soil without vegetation is to increase the overall runway resistance while keeping the overall shape of the speed vs $\mu$ curve.

For the case of the soil with vegetation the effect of rutting is different when compared with the case without it. Besides increasing the value of the overall resistance coefficient through the range of ground speed, the behaviour of the $\mu$ vs speed curve changes, approximating to the shape of the curve for the soil without vegetation. It may be understood as a transition phase between the case of runways with a virgin vegetation to a virgin soil.

### 5.4 The Effect of Aircraft Weight and Tyre Pressure

The aircraft weight and tyre pressure may impact the rolling resistance since it may cause different tyre sinkage on ground which is the principal driver of the compactation and bulldozing drag.

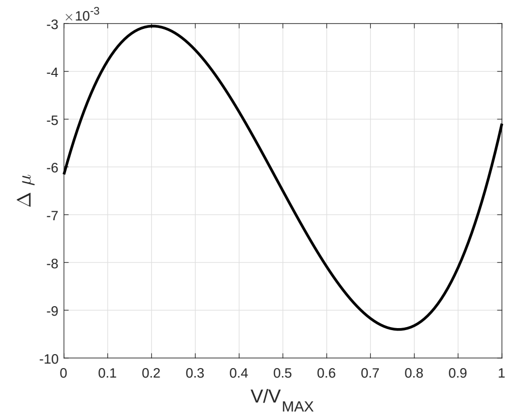


Figure 16: Example of the effect of -30 tons in aircraft weight.

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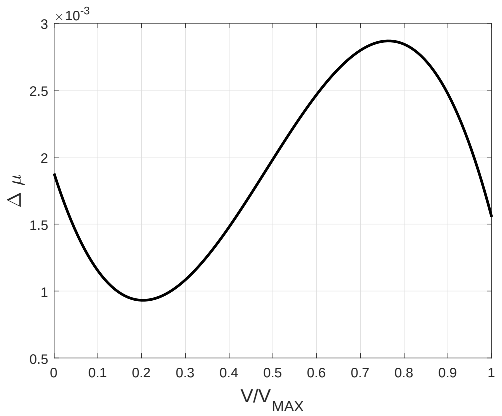


Figure 17: Example of the effect of 40 lb/in2 of tyre pressure.

In Fig. 16 and 17 the impact of -30 tons on the overall rolling resistance is a very small reduction in $\mu$, and the reduction in tyre pressure increases the rolling resistance but also with a very small impact.

These two figures may be understood as the overall design of landing gear architecture are linked to the aircraft operational weight, including the number of aircraft tyres. Therefore the small impact of weight and tyre pressure signals that although variations of these two parameters are possible, the overall tyre load transmitted to the ground, does not change significantly the overall compactation and bulldozing drag.

## 6. Rolling Drag Dimensional Analysis

The rolling resistance coefficient over unpaved runway presents the peculiar characteristics of being a function of the tyre sinkage and therefore many parameters affect the soil resistance such as the aircraft weight($W$), tyre pressure ($P$), ground speed ($V$) and the soil properties as the specific mass ($\rho$), the $CBR$ and the shear strength represented by the cohesion ($C$).

An attempt was made to correlate these variables using the Buckingham $\Pi$ theorem with 18 take-off tests over unpaved pavement with the objective of finding non dimensional groups which correlate in a simple mathematical relation to be used to predict the unpaved runway rolling resistance ($F_R$).

$$\begin{gathered} F_R = f(W, P, V, \rho, CBR, C) \\ \Pi_1 = \frac{F_R \cdot CBR}{W^{2/3} \cdot P^{1/3} \cdot V^{4/3}} \\ \Pi_2 = V \cdot \sqrt{\frac{\rho}{C}} \end{gathered} \tag{17}$$

Correlating these two groups ($\Pi_1$ and $\Pi_2$) for the 18 acceleration take-off tests, a mathematical correlation may be formed.

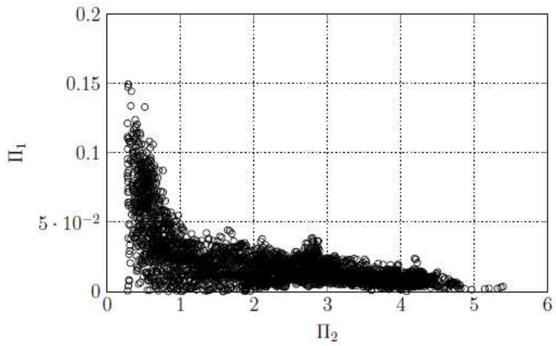


Figure 18: Relation between $\Pi_1$ and $\Pi_2$.

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The relation between the two groups shown in Fig. 18 may be better modelled as three separated functions.

$$\Pi_1 = \begin{cases} 0.0222 \cdot \Pi_2^{-1.067} & \text{if } \Pi_2 \leq 2 \\ 0.0289 \cdot \Pi_2^{-0.826} & \text{if } \Pi_2 < 4 \\ 0.261 \cdot \Pi_2^{-2.5} & \text{if } \Pi_2 \geq 4 \end{cases} \tag{18}$$

The model predicted in Eq. 18 may be used to assess the impact of each variable on the overall rolling resistance which may aid on the preliminary design of aircraft critical systems for unpaved runway operations and also it may enhance and optimize flight test planning.

## 7. Conclusion

In this work the challenges of modelling the rolling and braking resistance over unpaved runway was exposed together with the existing theoretical models and its limitations based on the soil mechanical properties and tyre mechanics. A methodology to expand and derive a resistance coefficient model to calculate aircraft performance was detailed and the resulting impact of CBR, ground speed, the presence of vegetation and rutting, aircraft weight and tyre pressure were outlined in where the correlation between CBR and rolling $\mu$ in the presence of vegetation was not evident and the effect of runway rutting tends to in overall increase the friction force regardless having vegetation or not. In the case of soil with vegetation and rutting, it may be understood as a transitioning model between the soil with virgin vegetation and without it. The impact of the aircraft weight and tyre pressure were found to be small and negligible when compared to other parameters. For the braking cases, every parameter, CBR, ruts, tyre pressure and aircraft weight does not seem to affect significantly the braking coefficient. The major effect is found in the braking coefficient and speed gradient in which for the cases without vegetation, it is higher, reaching maximum braking efficiency earlier when compared with braking performance over airfield with vegetation.

## 8. Acknowledgments

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