Numerical Prediction Model of Runway-Taxiway Junctions for Optimizing the Runway Evacuation Time

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Abstract. It is vital to ensure efficient and fast connection networks that guarantee the development of society in the global atmosphere. Air transport and airport operations play fundamental roles that help to achieve the needs of globalized society, constituting a pillar for providing essential services to a great number of passengers and goods around the world. In the coming years, air industry is expected to expand due to the imminent increase of passengers. This growth in air passenger journeys demands several measures to be applied in airports worldwide. Air traffic must comply with great levels of safety and efficiency according to existing standards to guarantee optimal airport operations. Moreover, airport infrastructures, such as runways and taxiways, should be continuously improved to minimize the possible costs and probability of associated risks, and to maximize their capacities by re-evaluating their designs to cope with the demands derived from the growth in traffic forecasted for the future.

In this regard, a prediction model to simulate the behavior of aircraft in landing was developed, allowing to predict the optimum locations of runway-taxiway junctions, enhancing the efficiency of the runway, and minimizing the runway evacuation time. This model is based on tire-fluid-pavement interactions that govern the dynamic behavior of the aircraft during landing in wet and dry pavement conditions. The results provide the accurate landing distance required for operating aircraft inside the airport, which can be used to design enhanced capacity runways, while guaranteeing the safety of operations by minimizing the related accidents probabilities.

Keywords: Runway-taxiway junction optimization · Runway capacity · Airport design

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1 Introduction

Due to the continuous international growth of society, air traffic is expected to experience a significant increase by the end of the next twenty years, in terms of passengers and goods [1]. However, this growth needs to be followed by the improvements in airport infrastructures and enhancement of their related services, in order to satisfy the expected market demands. Thus, it is necessary to continuously monitor the current needs of the airports and to predict the possible future requirements.

Safety and efficiency are main objectives in air transport operations that are required to be guaranteed by airport infrastructures such as runways and taxiways. These infrastructures should be continuously improved in order to minimize the related operations costs and the risks derived from their use. Different scientific studies and standards have been published worldwide trying to investigate possible solutions to these issues [2], evaluating the safe operations on runways and the different possibilities to manage the volume of passengers at airports worldwide. As a result, the efficiency of airports infrastructures can be maximized by re-evaluating their designs and characteristics and providing alternative design solutions in order to cope with the demands derived from the growth in traffic forecasted for the future.

In this context, runway and taxiway designs and their junctions are playing a vital role in determining the runway capacity, evacuation time, fuel consumption, and associated costs of related operations. Therefore, it is essential to develop a prediction model that offers optimized solutions of the taxiway junctions' locations according to the operating fleet.

Furthermore, landings are complex operations that nowadays contribute to one of the major phases of flights in which accidents occur with higher probabilities [3, 4]. Therefore, this study focused on the aircraft behavior during landings in order to provide a deeper understanding of the underlying physical principles which set the basis for the runway and taxiway designs.

2 Background Review and Scope

The available methods to predict the behavior of aircraft in landing are mainly based on empirical methods [5–7] and [8], which were trying to predict pavement friction based on models derived from experimental data [9, 10] and [11]. These approaches generally include the effects of pavement contamination (e.g. presence of water-film on pavement) in their computations. The main issue in the development of these methods is the lack of reference data regarding operating aircraft to be adopted in the simulations of these models. The results obtained in these experimental studies are tightly bounded to a strict range of values in final approach speeds, tire pressures and water-film thicknesses, which lead to major difficulties when the same approaches are required to be extrapolated to other areas of interest with values that fall out of range of those adopted by the original studies. Thus, the aim of this study is to extend those limitations, allowing to reach a deeper understanding and evaluating the influences of a wider range of involved parameters [12, 13].

Among analytical models available in literature, the one developed by Ong and Fwa [5, 6] was selected as a reference for this study. This model proposes a three-dimensional

approach based on Finite Element Analysis (FEA) using computational simulation, which integrate three sub-models of fluid, tire and pavement in order to analyze the relative influencing parameters that govern the dynamics of the operations. Consequently, it is possible to determine precisely the optimal distances of runway-taxiway junctions from the runway's threshold, according to numerous impact parameters such as airport climate pattern, operating aircraft categories, infrastructure type and capacity, route connections, and operating costs.

3 Methodology

Determining the most accurate model among the existing ones in the literature, which can portray the dynamic behavior of aircraft in landing, was one of the main challenges for this study. Most of the current available studies focused on experimentally derived empirical models due to simpler parameters to be considered in their methodologies. However, in this study a computational finite element model centered on a theoretical basis was developed, in order to simulate the interactions between aircraft tire, fluid, and different types of pavements.

The selected theoretical approach is based on the research conducted by Horne et al., published by NASA [9, 10]. In this context, the dynamic influences of the fluid forces acting on the main gear tire throughout the whole landing process can be evaluated.

In this regard, the crucial forces, which should be implemented in fluid equations, are the fluid drag and uplift forces, whose values vary with the change in aircraft velocity. The fluid drag force acting on the main gear tire in presence of various water-film thicknesses on the runway surface can be expressed for a single aircraft wheel as:

$$F_{drag} = \frac{1}{2} C_{Dh} \rho_w t_w f(w) V^2 \tag{1}$$

Where, F_{drag} stands for the fluid drag/retardation force; C_{Dh} represents the hydrodynamic drag coefficient; ρ_w is the water density; t_w is the water-film thickness; V stands for the aircraft speed; and $f(w)$ is a function which stands for the chord length of the tire cross section at the water surface, which has been presented by Horne et al. [9] as:

$$f(w) = 2w \left[\frac{\delta + t_w}{w} - \left(\frac{\delta + t_w}{w} \right)^2 \right]^{\frac{1}{2}} \tag{2}$$

Where, w stands for the tire width; and δ represents the vertical tire deflection. As a result, it can be deduced that the fluid drag force varies linearly respect to the fluid density and thickness, the tire width, and the landing velocity squared. It must be highlighted that in order to avoid higher complexity, this study considered the evaluation of the drag force for a single wheel or front mounted tandem wheel ignoring the effects of other possible landing gear components in the surroundings. Additionally, the possible effects induced by hydroplaning in the drag force are not considered for simplification purposes.

The fluid uplift force also generates a significant effect over the main gear tire, which can be the cause of the phenomena called hydroplaning in its higher values. This force,

which also needs to be modeled accurately, can be expressed for a single aircraft wheel as:

$$F_{uplift} = \frac{1}{2} C_{Lh} \rho_w A V^2 \tag{3}$$

Where, F_{uplift} stands for the fluid uplift force; C_{Lh} represents the hydrodynamic uplift coefficient; ρ_w is the water density; A is the tire-ground gross contact area; and V is the aircraft landing velocity. However, Eq. 3 only portrays the effect of the hydrodynamic pressure on the tire footprint area. According to [11], the front region of the water-film layer impacting the tire, known as the water wedge, needs to be considered as the hydrodynamic pressure in this region contributes also to the total vertical force. This way, this region is defined by the water wedge length l until the water reaches the tire footprint. If the effects of water spray are neglected, the effect of the hydrodynamic pressure in this region can be expressed through the Eq. 4.

$$F_{wedge} = w l \rho_w V^2 \tag{4}$$

Where F_{wedge} stands for the fluid uplift force in the wedge region; w represents the tire width, l is the length of the wedge; and V is the aircraft velocity. The length of wedge can be calculated by modeling the tire profile, as presented in Fig. 1.

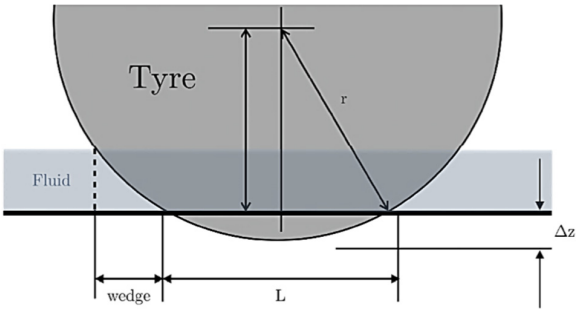


Fig. 1. Tire contact simplified model [14]

Finally, the overall vertical force acting on main gear tire can be computed by combining both contributions represented by Eqs. 3 and 4. This way, when the F_{uplift} equals the aircraft wheel load, it causes a complete loss of braking potential and consequently aircraft sliding with the wheel locked up on the existing water-film on the runway surface (i.e. hydroplaning phenomenon). Therefore, fluid uplift force has a great impact on the friction between tire and pavement in presence of water-film on the surface, and consequently on the final landing required distance. Both drag and uplift fluid forces have been used inside the developed model in order to predict the optimal locations of runway-taxiway junctions, as illustrated in Fig. 2.

After determining accurate models to evaluate the related fluid forces acting on the tire and pavement surface, a MATLAB®-based numerical model has been developed in order to simulate the dynamic behavior of aircraft in landing based on the aerodynamics

```
%% FLUID FORCES ON LANDING GEAR

pr = 0.25.*p_max; % rated tire inflation pressure [Pa]

delta = Fz./(2.4.*(p+0.08.*pr).*(w.*d).^(1/2)) + w.*C_z; % vertical tire
f_w   = 2.*w.*(((delta+dL)./w)-((delta+dL)./w).^2).^(1/2);

F_drag = 1/2.*CD_h.*rho_water.*dL.*f_w.*V.^2; % Fluid drag force [N]

 F_uplift = rho_water.*V.^2.*(A_G.*CL_h.*0.5+ x_under.*w);
```

Fig. 2. A part of developed numerical script to compute the fluid drag and uplift forces

of the aircraft components, their structural mechanics, and the fluid dynamics based on the guidelines established previously by Ong et al. [5, 6], Pasindu et al. [15] and Ketabdari et al. [16, 17], as illustrated in Fig. 3.

```
 while V(i)> exit_velocity

 % Obtain the SNv for each timestep
 [SNv] = computation_SNv_NASA_distribution(aircraft,V(i),dL,L_average);

 % dynamic friction coefficient
 mu = SNv./100;

 % deceleration rate
 a = mu.*g + (0.5.*rho_air.*V(i).^2.*A.*(CD-mu.*CL))/(W);
 V_next = V(i) - a.*dt;

 delta_v = V(i) - V_next;
 delta_x = delta_v.*dt;

 V_vector(i,counter) = V(i);

 V(i) = V_next;

 % distance travelled on one interation
 x(i,counter) = x0 + V(i).*dt;
 t(counter) = t(end) + dt;
 x0 = x(i,counter);


 counter = counter + 1;
 end
end
```

Fig. 3. A part of developed numerical script to compute the aircraft braking distance in landing

4 Validation

In order to evaluate the accuracy of the developed model results for computing the dynamic skid resistance in wet pavement, and to evaluate the model's reliability for aircraft tires, a preliminary validation study has been performed. In this procedure, the

skid resistance values obtained by the developed computation model were compared to the experimental data extracted from Horne et al. study [18] to check the applicability of the selected approaches. The conditions set for this validation process are gathered in Table 1.

Table 1. Boundary conditions set for validation process of skid resistance model

Tire dimensions	Tire type	Wheel load	Water-film thickness	Inflation pressure
32 × 8.8 inches	VII	9979 kg	3.8 mm	1999.5 kPa

Two types of pavements were considered in the computations of this study; rigid pavement runway (i.e. concrete) with tested sliding speed range from 10 to 40 m/s; and flexible pavement runway (i.e. asphalt) with tested sliding speeds range from 10 to 50 m/s. The extracted experimental Skid Number values (SNv) and those obtained by the developed model of this study are presented in Table 2.

Table 2. Skid number values computed versus those collected from literature

V (m/s)	SNv (literature)		SNv computed (model)		Percentage error (%)	
	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt
10	23	39	21	36.5	−8.7	−6.4
20	20	34	19.5	33.5	−2.5	−1.4
30	16.5	29	17	30	+3.0	+3.4
40	13	24	14	24.5	+7.7	+2.1
50	–	19	–	17.5	–	−7.9

As it can be interpreted from Table 2, the SN values obtained for asphalt and concrete pavements from the developed computation models present sufficient similarity to those extracted from the literature [18], which can guarantee a significant accuracy of the developed fluid-tire-pavement interaction model. The absolute percentage errors obtained for the predictions were resulted below ±9% with low numerical differences. Therefore, it can be stated that the chosen methodology constitutes a suitable approach for the simulation of the behavior of aircraft tires over the wet runway pavement.

5 Traffic Data and Aircraft Classification

Once the applicability of the methodology has been validated, it is possible to find a solution for the taxiway design. Nevertheless, in order to provide an efficient solution, a database of operating aircraft should be provided to be adopted by the model.

These data can consist of commercial airplanes and general aviation. The characteristics of the aircraft belonging to these two categories generally differ from each other in term of dimension, weight, fuel consumption, and operation costs, however, both categories are assumed to operate on the same runway. Therefore, same simulation steps and circumstances should be applied on both aircraft categories.

According to the simulation model described in previous sections, the main technical specifications of aircraft that are required in the proposed prediction model are Maximum Landing Weight (MLW), landing gear arrangement, tire inflation pressure, tire dimensions, aerodynamic lift and drag coefficients, final approach speed (V), and wing area (S). These data are generally available through the Airport Planning Manuals (APMs) or reliable aircraft database sources such as BADA-Eurocontrol [19], and Aircraft Performance Database (APD) [20].

The database used for the simulations is composed by 95 aircraft, classified into different groups based on their final approach speeds, according to the criteria established by ICAO [21]. In Table 3 a partial list of these aircraft is presented.

Table 3. A partial preview of provided aircraft database to be adopted by the proposed model

Operating aircraft	Aircraft category	MLW (kg)	V (m/s)	S (m^2)
Airbus A319	C	62500	64,82	122,60
Airbus A320	C	66000	69,96	122,60
Embraer 175	C	34000	63,79	72,72
Embraer 190	C	43000	63,79	92,53
Boeing 737-800 Winglets	D	65317	73,05	124,65
Airbus A320 Sharklets	C	66000	69,96	122,60
Airbus A321	D	75500	72,02	122,60
Boeing 737-700 Winglets	C	58060	66,88	124,65
McDonnell Douglas MD-82	C	58967	68,93	112,32
Airbus A318	C	57500	62,25	122,60
Boeing 737-400	C	56245	71,51	91,09
Boeing 737-300	C	51710	68,42	91,09
Boeing 737-800	D	65317	73,05	124,65
McDonnell Douglas MD-83	D	63276	74,08	112,32
De Havilland DHC-8 (8-400)	B	28009	62,63	63,10
ATR 72	B	22350	58,65	61,00
Embraer Brasilia E120	A	11700	58,13	39,40

According to ICAO [21], aircraft should be classified respect to their final approach/threshold speeds. This way, four official groups can be formed: group A comprises those aircraft with final approach speeds lower than 91 kts (46 m/s); group B comprises

those whose speeds are higher than 91 kts and lower or equal to 121 kts (61 m/s); group C comprises the models with speeds ranging from 122 kts to 140 kts (72 m/s); and group D includes those models with final approach speeds higher than 141 kts up to 165 kts (85 m/s). As a result, four groups are established, as presented in Fig. 4.

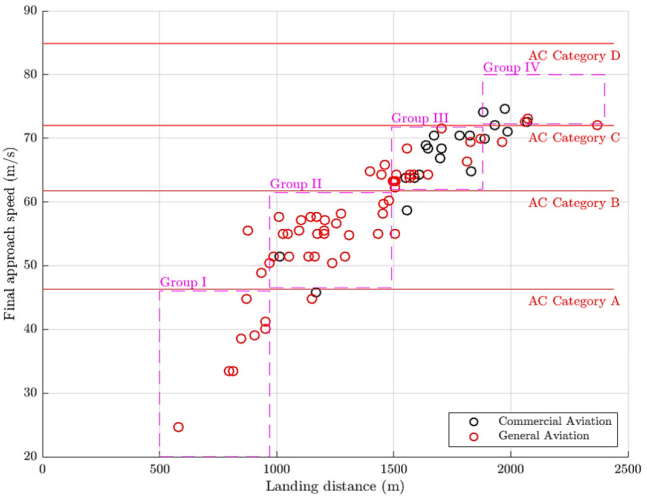


Fig. 4. Aircraft categorisation based on final approach speeds

6 Results and Discussion

The inputs required to be adopted in the simulation process as the boundary conditions of this study are air density (ρ: 1.225 kg/m^3), water density at 25 ℃ (ρ_w: 997.1 kg/m^3), landing speed reduction (k_s: 2 m/s), water-film thickness (t_w: 3 mm), dry friction coefficient (μ: 0.5), flap induced drag variation (Δf: 0.12), and runway exit speed (V_{exit}: 30 kts).

Based on the selected boundary conditions and aircraft categorization approach, the proposed model can simulate the aircraft behavior in landing operations for wet and dry pavement scenarios. The results will be used in numerical prediction of the locations of taxiway exits with optimal operations capacity for the airport design.

The behavior of aircraft in landing can be predicted by calculating the aircraft Landing Distance Required (LDR). Once the LDRs of selected operating aircraft are computed based on the finite element model explained in methodology chapter, an individual Optimal Turn-off Point (OTP) for each of these aircraft will be determined, which are needed in order to determine the closest location of runway exit junction.

As a result of simulations of landing aircraft behavior for selected operating aircraft (Table 3) through proposed model, the predicted locations of runway-taxiway junctions for wet and dry pavement scenarios are presented in Figs. 5 and 6. It is assumed that the landing direction is to be only from left toward right designation. According to ICAO

[21], a minimum separation of 450 m should be guaranteed between parallel runway exits.

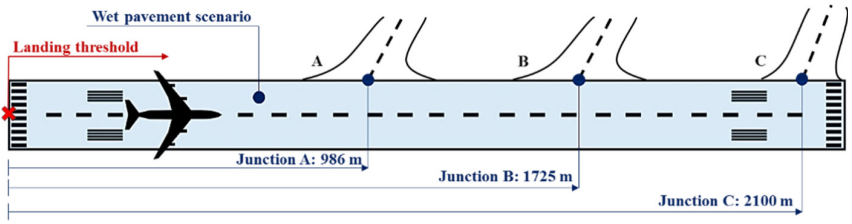


Fig. 5. Predicted optimal locations of three runway-taxiway junctions for designing a runway in wet pavement scenario (not to scale)

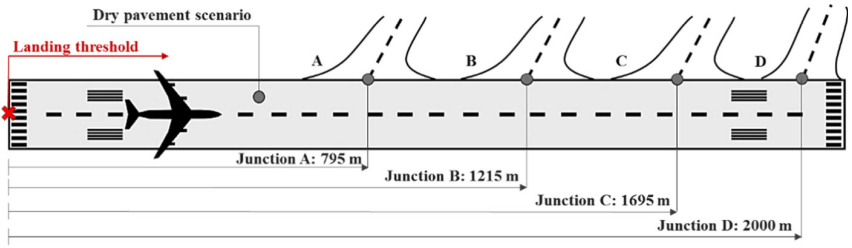


Fig. 6. Predicted optimal locations of four runway-taxiway junctions for designing a runway in dry pavement scenario (not to scale)

In dry pavement scenario, shorter landing distances resulted in an accumulation of OTPs over areas closer to the runway landing threshold respect to the wet pavement scenario.

Aircraft mean rolling distances can be calculated in order to evaluate the effectivity of both proposed solutions. These distances are defined as the travelled distance from each individual OTP to the actual runway exit. Lower rolling distances will logically lead to lower evacuation times. Therefore, thanks to OTP calculations, it is possible to maximize the runway capacity and performance level, which would increase the number of operations. These mean rolling distances related to the predicted locations of proposed model (proposed configurations) should be compared with common runway taxiway configurations for selected operating aircraft, in order to evaluate the solutions efficiency. Therefore, current runway-taxiway configuration of an Italian international airport was selected for comparative purposes, and the results are presented in Table 4.

As it can be interpreted from the obtained results, new runway-taxiway configurations for both wet and dry surfaces offer improvements respect to the common runway configurations in term of reduction in mean rolling distances and consequently reduction in total runway evacuation time. A reduction of 27% (95 m) for wet pavement condition and a reduction of 42% (149 m) for dry pavement condition have been registered in mean rolling distances for landing operations.

Table 4. Calculated mean rolling distances for wet and dry pavement scenarios

Results	Mean rolling distance		Distance variation		Percentage variation	
	Wet	Dry	Wet	Dry	Wet	Dry
Proposed configurations	275 m	207 m	−95 m	−149 m	−27%	−42%
Existing configurations	370 m	356 m				

7 Conclusion

The accurate estimation of the aircraft landing distances constitutes a complex process in which diverse parameters of different nature play significant roles. The main scope of this study was to develop a precise numerical prediction model to simulate the interactions between tire-fluid-pavement during landing phase of flight and finally offers a possibility to extrapolate this methodology and apply it on different airports with various boundary conditions.

This study is a complementary work to the previous attempts by the authors [15, 16], which had to face different criticalities encountered during the model development stages, such as lack of precise reference models and complete experimental databases. In this study, the prediction model, which is based on the analysis of pavement friction and fluid properties, has been developed by adopting the equations offered by Horne et al. [9, 10] and Sinnamon et al. [11], providing an alternative way to the existing models proposed by Ong et al. [5, 6], Pasindu et al. [15], and finally validated according to existing experimental data from available literature [18].

The developed model can simulate the aircraft dynamic behavior in landing operations for wet and dry pavement conditions. As a result of the simulation, LDR for aircraft in dry pavement condition demonstrate noticeable shorter values respect to the values for wet pavement, which clarify the conspicuous impact of contaminants over the runway surface.

Eventually, the proposed methodology successfully proved to be a valid approach in order to calculate the accurate aircraft braking distance in landing phase of flight, which can be adopted for commercial airports with various types of operating aircraft to perform similar studies, trying to optimize the operation capacity of their infrastructures (e.g. runways and taxiways). Therefore, it will constitute one of the possible ways to improve the safety and efficiency of the operations, and to achieve noticeable reductions in terms of overall airport operations costs and infrastructures evacuation times, while ensuring and matching the needs of growth in air passenger journeys and goods freight demands.

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