

ASSESSING THE IMPACT OF THE SLOPES ON RUNWAY DRAINAGE CAPACITY BASED ON WHEEL/PATH SURFACE ADHESION CONDITIONS

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Abstract. Aircraft braking distance is dependent on the friction between the main gear tires and runway pavement surface. Pavement texture, which is divided into macrotexture and micro-texture, has a noticeable effect upon friction, especially when the surface is wet. A risk analysis framework is developed to study the effects of longitudinal and transverse slopes on the aircraft braking distance in wet runway conditions and their influences on the probability of landing overrun accidents. This framework is operating under various water-film thicknesses, Maximum Landing Weights (MLW), and touchdown speed probability distributions for an acceptable range of longitudinal/transverse slopes and pavement texture depths. A simulator code is developed that initially computes the existing water-film thickness, as the result of intense precipitation, under aircraft main gear (depend on aircraft category) and then applies this variable as one of the main inputs to the aircraft braking distance computation. According to the obtained results, longitudinal gradient does not have a significant effect on the existing water depth on the surface although it affects the flow path length. Furthermore, 1% to 1.5% transverse slope causes rapid drainage of water from the runway surface and considerably decreases the probability of runway excursion accidents.

Keywords: longitudinal and transverse slopes, pavement texture depth, drainage capacity, water-film thickness, aircraft braking distance, airport risk analysis.

Introduction

Runway-related incidents/accidents based on aircraft operations can be categorized as incursions and excursions. Incursions are dedicated to all events happening inside the runway (e.g. existence of an obstacle or accident of two aircrafts) and excursions are assigned to aircraft unsuccessful operations, which leads to surpassing the designated thresholds/borders of the runway. Among all types of excursion events, landing and take-off overruns are responsible for the major portions (Ketabdari et al., 2018). Many parameters and variables can affect the probability of occurrences of these events such as weather conditions, aircraft braking potential, pilot's experiences, etc. Although human errors (e.g. pilots incapability, etc.) are crucial reasons that amplify the probability of accidents, the scope of this study is investigating the effect of longitudinal and transverse slopes on the aircrafts braking potentials in wet pavement condition and how cross slopes may affect the occurrence probability of accidents.

Aircraft braking distance has direct relationship with the friction between the aircraft main gear wheels and runway pavement surface. In this regard, less friction causes lower aircraft braking potential, therefore, longer braking distance. Coefficient of friction (μ) stands for friction force (F) between two surfaces in contact and the normal force (N) exists in between, and can be evaluated by dividing F by N . μ depends on physical characteristics of the surfaces which are in contact, the temperature at the contact area and movement speed of the tire over the pavement.

Runway surface friction for a specific category of aircraft is directly proportional to the aircraft braking potential, which depends on wheel lock-up activation and equipped anti-skid protection systems. Moreover, runway surface texture has a considerable effect upon friction, especially when the surface is wet. The adherence and texture of the pavement can be divided into the following categories:

- Macrotexture is visible roughness that allows existing water on the pavement escape from beneath the aircraft tires. This category of adherence and texture

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is crucial in hydroplaning effect when aircraft landing touchdown speed increases and/or tire tread depth decreases and/or water depth increases;

- Micro-texture is fine scale roughness that associates with small individual aggregate particles. It is detectable by touch rather than appearance and allows the aircraft tire to break through the residual water-film on the pavement after running off the main volume of water because of the runway slopes. This parameter is especially crucial at low speeds.

In order to obtain an acceptable pavement texture for runway operations, extra attention should be paid to the finishing processes for a new runway surface. Runway surface friction, where challenged by water contamination, can be enhanced by various mitigation strategies for design phase of a new runway (e.g. transverse/longitudinal runway slopes) or in maintenance phase of an existing pavement (e.g. transverse/longitudinal grooving) to aid more rapid water dispersal.

A probabilistic risk analysis framework is developed to study the influence of longitudinal and transverse slopes on the probability of occurrence of landing overrun incidents/accidents in wet/dry runway conditions. This framework is simulating the aircraft braking distances for different; Water-Film Thicknesses (WFT) on the runway, aircraft Maximum Landing Weights (MLW), touchdown speed probability distributions for a range of longitudinal/transverse slopes, and Mean Texture Depths (MTD) of pavement.

1. Literature review

Risk assessment is a measurement of the frequency of occurrence of a hazardous event and evaluating the severity of possible consequences (Ketabdari et al., 2019). In other words, it is a process that consists of hazard identification, vulnerability assessment and system exposure evaluation. Different aviation risk models have been developed in past decades in order to assess quantitatively and qualitatively the risks associated with runway operations. To evaluate the effect of longitudinal/transverse slopes on

runway drainage capacity, several studies have been carried out in past decades, each of which has identified its own calculation methodology to predict the WFT. These prediction models are generally dependent on rainfall intensity, pavement material and texture, transverse and longitudinal slopes. The structure of these models can be classified as empirical and analytical. Empirical PAVDRN model (American Association of State Highway and Transportation Officials (AASHTO), 1990), Gallaway model (Gallaway et al., 1979) and New Zealand modified equation (Chesterton et al., 2006) are examples of widely used empirical models. Analytical PAVDRN model (Chesterton et al., 2006), which was developed by finite-element simulation, is an example of analytical models.

Numerous models have been developed previously in order to predict WFT with empirical or analytical methodologies, but in order to evaluate which of them are more accurate and functional to be selected in the computations, in 2019, a study was developed to validate the effectiveness of various WFT prediction models through field test data (Luo et al., 2019). In Table 1, a summary of the most accurate models according to this study is presented.

Where, *WFT*: Water Film Thickness [mm]; *I*: rainfall intensity [mm/h]; *MTD*: Mean Texture Depth [mm]; *L*: longest flow path length [m]; *S*: drainage slope [m/m]; and *n*: Manning’s roughness coefficient.

In another study in 2014, a computer model with a graphical user interface was developed for determining the risk of hydroplaning on a given roadway section under known wet weather conditions (Jayasooriya & Gunaratne, 2014). Different *WFT* prediction models have been used in the same study to simulate the hydroplaning risk of specific case study pavement and finally the same combination of models presented in Table 1 were suggested to be used to predict the *WFT*.

Therefore, the mentioned models in Table 1 are selected in this study as the principle models for predicting *WFT*. Among all, the corresponding empirical formula, developed by American Association of State Highway and Transportation Officials (AASHTO), is implemented in the computations of this study.

Table 1. Summary of the most common WFT prediction models (Luo et al., 2019)

Model	Reference	Category	Equation
Empirical PAVDRN	(AASHTO, 1990)	Empirical	$WFT = \left(0.00073 \times L^{0.519} \times I^{0.562} \times \frac{MTD^{0.125}}{S^{0.364}} \right) - MTD$
Gallaway	(Gallaway, 1979)	Empirical	$WFT = \left(0.01485 \times L^{0.43} \times I^{0.59} \times \frac{MTD^{0.11}}{S^{0.42}} \right) - MTD$
Modified New Zealand	(Chesterton et al., 2006)	Empirical	$WFT = \left(0.003264 \times L^{0.316} \times \frac{I^{0.2712}}{S^{0.3}} \right) - MTD$
Analytical PAVDRN	(Chesterton et al., 2006)	Analytical	$WFT = \left(n \times L \times \frac{I}{105.425 \times S^{0.5}} \right)^{0.6} - MTD$

In 2019, a finite element model was developed in order to compute aircraft braking distance for a runway with zero transverse and longitudinal slopes by the authors (Ketabdari et al., 2019). This MATLAB-based model is simulating the footprint of aircraft main gear and its interaction with the pavement for different water-film thicknesses existing on the runway. Developed tire-pavement interface model is computing dynamic skid resistances between the aircraft tire and the runway surface and adopts these values in computing the aircraft full stop Probability Density Function (PDF). This model is valid for a wide spectrum of aircraft categories with various Maximum Take-Off Weights (MTOWs) and wingspans.

In the beginning of 2020, the abovementioned model has been used by the authors (Ketabdari et al., 2020a) to design strategies to mitigate the severity of consequences of landing overrun events, but yet possible effects of runway slopes have not been considered in the study.

Therefore, current study is an update to this model, that by adopting empirical formula developed by AASHTO, the water film thickness for a runway with any transverse and longitudinal slopes can be now evaluated and consequently aircraft braking distance PDF for wet pavement operations can be computed.

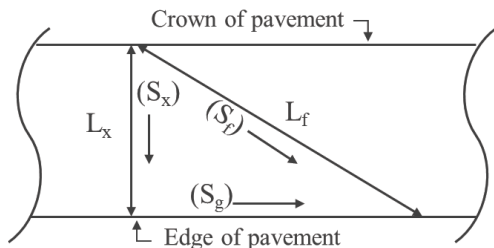
2. Flow mechanics of water-film behaviour on the runway surface

After rain drops fall on a sloped pavement surface, the runoff takes a path to the pavement edge, which is called the resultant flow path and its length (L_f) and its slope (S_f), as presented in Figure 1, can be determined as following (American Association of State Highway and Transportation Officials (AASHTO), 1992):

$$S_f = (S_x^2 + S_g^2)^{0.5} = S_x \times \left(1 + \left(\frac{S_g}{S_x} \right)^2 \right)^{0.5}; \quad (1)$$

$$L_f = L_x \times \left(\frac{S_f}{S_x} \right) = L_x \times \left(1 + \left(\frac{S_g}{S_x} \right)^2 \right)^{0.5}, \quad (2)$$

where, S_x is the runway transverse slope; S_g is the runway longitudinal gradient; S_f is the resultant water-film flow path slope; L_x is runway width [m]; and L_f is the length of water-film flow path [m].



As it can be seen from Figure 1 and Equation 2, by increasing L_x or by steepening S_g , L_f will be increased. In order to increase the precision of calculation, in this study instead of L_x , the actual main gear contact width (L_{cw}) is adopted which can be evaluated according to section 4.2. WFT , which accumulates on the runway, depends on rainfall intensity (I), L_f , S_f and MTD of the runway surface (AASHTO, 1992). MTD is a measure of the roughness (macrotexture) of the pavement and can be determined by volumetric patch method. The empirical equation in order to predict the WFT , based on a regression analysis of experimental data, can be written as:

$$WFT = \left(0.00338 \times MTD^{0.11} \times L_f^{0.43} \times I^{0.59} \times S_f^{-0.42} \right) - MTD, \quad (3)$$

where, L_f is the length of flow path [ft.]; I is the intensity of rainfall [in/h]; MTD is in [in]; and S_f is the slope of flow path [ft./ft.].

According to Equation 3, longitudinal gradient does not have a significant effect on the water depth although it affects the flow path length. It may be useful to note that as the longitudinal gradient is steepened and the flow path lengthened, the flow velocity also increases because of the increase in the resultant slope, thereby offsetting the tendency for an increase in the water depth. The judgement on this matter is that the longitudinal gradient does not have an appreciable effect on the water depth on the runway (AASHTO, 1992).

3. Aircraft braking distance methodology

A wide variety of parameters involve in calculation of aircrafts braking distances and the consequent stoppage locations (e.g. phase of flight, aerodynamic drag and uplift forces, headwind/tailwind, aircraft braking potential, reverse thrust, dry/wet runway, touchdown speed, etc.) (Ketabdari et al., 2019). In 2004, a numerical simulation has been proposed based on finite-element analysis to compute friction between tire and pavement without considering tire-fluid interaction (Li et al., 2004; Eshel, 1967). In 2007, a three-dimensional finite element model was developed in order to evaluate the skid resistance of runway pavement in wet conditions (Ong & Fwa, 2007; Grogger & Weiss, 1996). By taking advantage of this model, following algorithm (see Figure 2) is developed in order to evaluate the braking distance of a selected set of aircraft categories.

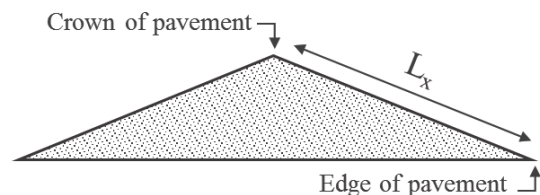


Figure 1. Definition scheme of runway transverse/longitudinal slopes (Guvén & Melville, 1999)

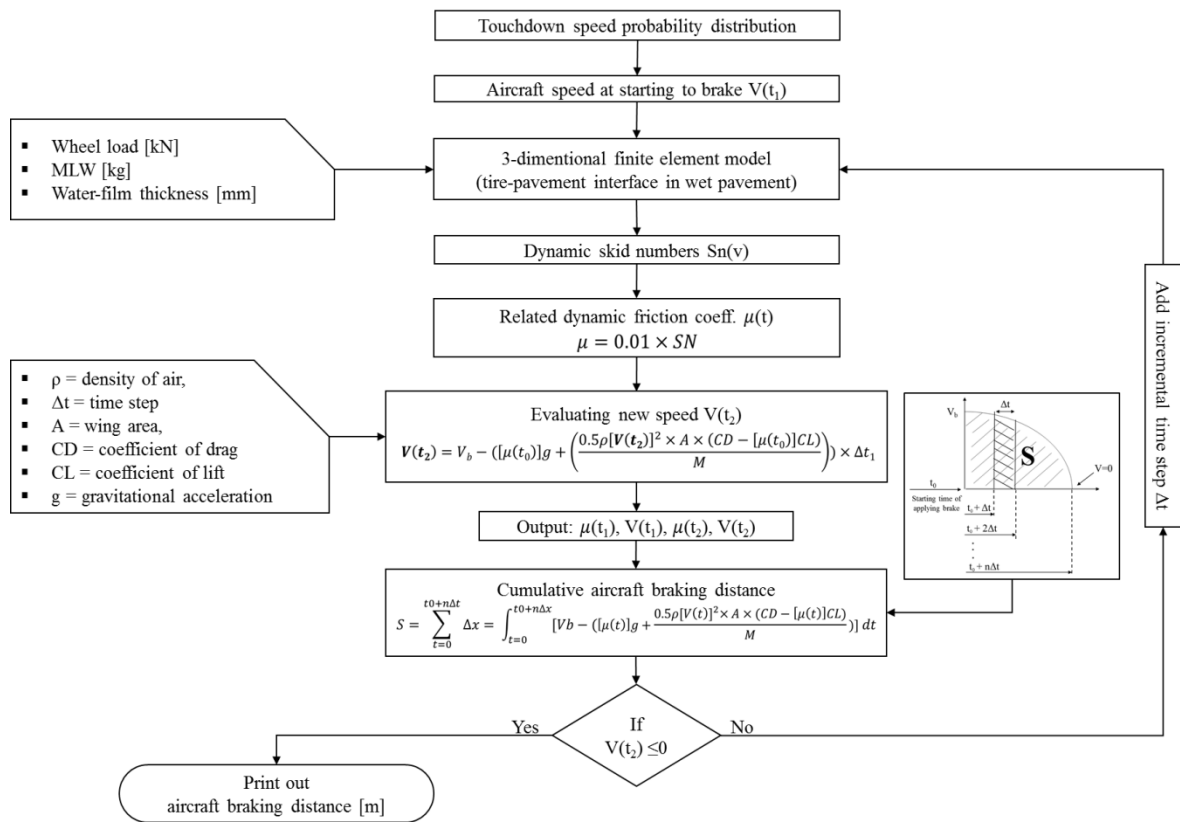


Figure 2. Aircraft braking distance developed algorithm in wet pavement conditions

In order to evaluate the aircraft braking distance in the condition of wet pavement and existence of longitudinal and transverse slopes, a simulator code is developed that initially compute the existing *WFT* on the runway pavement under aircraft main gear (depend on aircraft category) and then applies this variable as one of the main inputs to the aforementioned algorithm.

4. Models assumptions and boundary conditions

4.1. Rainfall intensity

Rainfall intensity, which can be calculated by dividing the rainfall depth for a given period by the total duration of the period (mm/h), is classified according to the rate of precipitation (Monjo, 2016). This classification is as follows:

- Light rain; Precipitation Rate (PR) < 2.5 mm/h (0.098 in/h);
- Moderate rain; 2.5 mm/h (0.098 in/h) < PR < 7.6 mm/h (0.30 in/h);
- Heavy rain; 7.6 mm/h (0.30 in/h) < PR < 50 mm/h (2.0 in/h);
- Violent rain; PR > 50 mm/h (2.0 in/h) (American Meteorological Society, 2000).

Violent rain classification with 100 mm/h rate of precipitation is considered for the rainfall intensity in order to evaluate the worst-case scenario, which leads to thicker water-film accumulation on the runway surface. The be-

haviour of water flow during hydroplaning is assumed to be laminar and not turbulent (Okano & Koishi, 2001).

4.2. Aircraft characteristics and conditions

Different aerodrome reference codes are derived from the most restrictive of either the aircraft wingspan or the aircraft Outer Main Gear Wheel Span (OMGWS) by International Civil Aviation Organization (ICAO) to assign to aircrafts. This categorization simplifies the process of establishing whether an aircraft can use a specific aerodrome or not (ICAO, 2013). In Table 2, top commercial and military aircrafts with the widest OMGWS are provided.

As it can be interpreted from the Table 2, longest OMGWS, which is the distance between the outside edges of the main gear wheels (ICAO, 2013), is 14.34 m (approx. 15 m). In order to simulate the actual main gear contact width (L_{CW}) for a set of aircraft categories, Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD v1.42) software is adopted. This software is the standard reference program to design the airport pavement thickness that is provided by Federal Aviation Administration (FAA). Thanks to this software, lateral landing load distributions of critical aircrafts that are operating daily according to the selected case study airport, are simulated and presented in Figure 3.

As it can be observed, the actual L_{CW} can be involved almost 8 meters on each sides of the runway centerline. Therefore, respect to the achieved results from Table 2 and

Table 2. Selected commercial and military aircrafts with the widest OMGWS

Aircraft	Code letter	OMGWS [m]	Wing Span [m]	Type
A380	F	14.34	79.75	Commercial
B-2 Spirit	E	13.16	52.43	Military
B777	E	12.90	60.93	Commercial
A350	E	12.87	64.74	Commercial
B747-8	F	12.73	68.40	Commercial
MD10	D	12.65	47.34	Commercial
B747-400ER	E	12.62	64.92	Commercial
A340-600	E	12.61	63.45	Commercial
A330-300	E	12.61	60.30	Commercial
MD11	D	12.57	51.99	Commercial
KC10	D	12.56	50.39	Military
B787	E	11.90	60.12	Commercial
MRA4	D	11.54	38.07	Military
C-5 Galaxy	F	11.44	67.88	Military
KC-46	D	10.90	47.57	Military
B767	D	10.90	47.57	Commercial

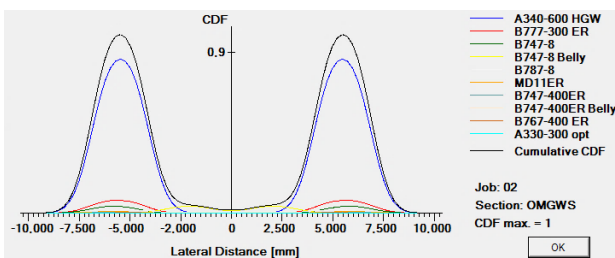


Figure 3. Aircraft lateral landing load distributions simulated by FAARFIELD v1.42

Figure 3, 16 meters is selected as an average L_{CW} in order to be implemented in the calculation of runway drainage capacity and consequence aircraft braking distance. In addition, this set of computation is carried out for all the selected aircraft presented in Table 2.

Regard to previous studies (Hosang, 1975; Barnes et al., 1998), aircraft speed at the touchdown is known to be vary and not one specific number (Pasindu et al., 2011). Therefore, aircraft touchdown speed is considered as normal probability distribution because of its random variable characteristics. It should be noted that although these previous studies were developed before year 2000, they are considered as principal references in this field and because of their novelty and originality they are adopted in this study.

The effect of reverse thrust is not considered in the calculation of braking distance. Moreover, a locked-wheel condition was assumed for the aircraft wheel running over a water-film on the runway surface. This means that after

initiation of braking by the pilot, tires stop rotating and just slide in the runway surface because of water on the pavement. This fact led considering the worst-case scenario since friction is minimized in the condition of locked wheel (Ketabdari et al., 2020b). Headwind and tailwind forces are also applied on the aircraft during braking procedure.

Aircraft braking distance on the cumulated WFT in the presence of selected transverse slope can be calculated based on this study. Since the longitudinal gradient has a negligible influence on the drainage capacity of the runway (Guyen & Melville, 1999), a constant longitudinal slope [1%] is considered for the developed methodology. Furthermore, Hot Mix Asphalt (HMA) and concrete pavement materials are considered to cover both flexible and rigid pavements.

Landing touchdown speed for different categories of aircrafts varies according to their MLWs and runway condition. In the calculations, this speed should be investigated vertically and horizontally. Since the effect of vertical landing speed on the braking distance is negligible, horizontal one should be considered.

4.3. Runway characteristics and criteria

According to European Aviation Safety Agency (EASA), rapid drainage of water from the runway surface is the main safety scope of the runway transverse slope and the main objective of limiting the longitudinal runway slope is to have stable and safe operations by an aircraft on runway (European Aviation Safety Agency, 2017). It is suggested to choose the transverse slope:

- Between 1% and 1.5% for aerodrome reference code letters of C, D, E or F;
- Between 1% and 2% for aerodrome reference code letters of A or B.

It is also suggested to implement flatter slopes for the intersections of runway and taxiway (European Aviation Safety Agency, 2017). The selected aircraft categories have wingspan greater than 36 m, therefore the related aerodrome reference code letters are C, D, E or F. In this regard, the runway transverse slope should be considered between 1% and 1.5%. In order to determine the impact of transverse slope on the drainage capacity of the runway values of 0.5%, 1.5% and 2.5% are considered in the evaluations. Based on the topography of the airport, local precipitation rate and operating aircraft categories, transverse slopes can be executed by two types, which are presented in Figure 4:

- Single-pitched transverse slope; existing water-film on the runway drains from one lateral drainage system;
- Double-pitched transverse slope; for a cambered surface, the transverse slopes on each side of the centreline should be symmetrical.

It should be noted that for both types, the transverse slope should not be modified throughout the whole runway length except at taxiways junctions. In that condition, an even transition should be provided taking account of

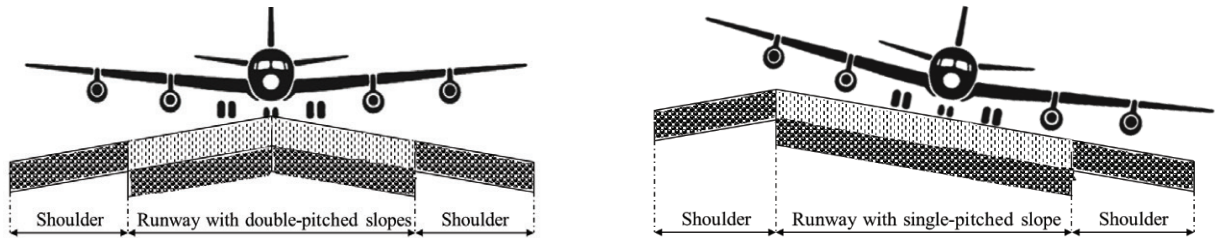


Figure 4. Execution methods of runway transverse slopes; doubled-pitched and single-pitched

the need for adequate drainage. In this study, double-pitched transverse slopes are considered according to the fact that highly operative runways are usually designed in this way and single-pitched transverse slope is adopted for taxiways or runways with low annual operations rate.

According to the definition of the longitudinal slope by EASA, it can be computed by dividing the difference between the maximum and minimum elevation throughout the runway length along the runway centreline (European Aviation Safety Agency, 2017). It is suggested that the value of the longitudinal slope should be limited to:

- 1% for aerodrome reference code numbers of 3 or 4;
- 2% for aerodrome reference code numbers of 1 or 2.

According to CS ADR-DSN, section B.045, if the operating aircrafts on the runway have OMGWS between 9 and 16 meters, the acceptable aerodrome reference code numbers will be 3 or 4 (European Aviation Safety Agency, 2017). In order to investigate the worst-case scenario, in this study, aircrafts with widest OMGWS have been chosen as previously mentioned. Therefore, the acceptable aerodrome reference code numbers are 3 or 4, which means the longitudinal slope should be limited to 1%.

Another required variable in evaluation of pavement drainage capacity is macrotexture depth. Volumetric patch method (sand patch method) is generally recognized as one of the most suitable techniques available for measuring this variable. In this method, in order to compute the macrotexture depth with acceptable degree of precision, a known volume of sand particles with specific grading is spread over the pavement surface until all the cavities are filled (ICAO, 2002). Equation 4 is used in order to calculate the texture depth of the runway pavement surface.

$$TD = \text{Texture depth (mm)} = \frac{\text{Volume of sand (mm}^3\text{)}}{\text{Area covered by sand (mm}^2\text{)}} \quad (4)$$

According to ICAO Annex 14, for a new pavement surface it is recommended to have an average macrotexture depth higher than 1 mm in order to provide adequate friction in wet-pavement runway. Although a depth of less than 1 mm can still provide good drainage, maintenance action may soon be required (ICAO, 2013). In order to make sensitivity analyses on the impact of texture depth on the drainage capacity of the sloped runway, MTDs 0.5, 1 and 1.5 are evaluated as the results of sand patch method.

5. Results and discussion

In order to evaluate the aircraft braking distance through the developed simulator code, numerous variables should be selected as inputs. These variables are divided into the following categories:

1. Aircraft characteristics:
 - Aircraft category (e.g. medium [ICAO], large [FAA]);
 - Range of operative OMGWS (e.g. 16 m in total, 8 m each slope side (L_x));
 - MLW (e.g. 40000 kg);
 - Main gear load (e.g. 50 kN);
 - Wingspan/wing area (e.g. 54 m²);
 - Coefficient of Drag – CD (e.g. 0.08);
 - Coefficient of Lift – CL (e.g. 0.95).
2. Weather and runway conditions:
 - Headwind (e.g. –2 m/s) and tailwind (e.g. +5 m/s);
 - WFT existing on runway (taken from Table 3, e.g. 4.22 mm);
 - Dry friction coefficient (e.g. 0.5);
 - Rain intensity (e.g. violent rain: 100 mm/h rate of precipitation);
 - Asphalt/concrete friction coefficients (e.g. 0.375).
3. Probability distribution of landing touchdown speed:
 - Maximum/minimum possible touchdown speed;
 - Mean value of touchdown velocity normal distribution (e.g. 55 m/s);
 - Variance of touchdown velocity normal distribution (e.g. 7 m/s);
 - Discretization of projected time (e.g. 0.3 s).

Based on the OMGWS, the contact width between the main gear tire and runway surface for each aircraft (L_{cw}) is outputted by FAARFIELD v1.42. This value should be considered as runway width (L_x). The obtained values plus the selected transverse and longitudinal slopes are inputted inside the formulas 1, 2 and 3 respectively to evaluate the flow mechanics of the water-film and to compute the existing WFT to be inserted in the developed braking distance simulator code. In Table 3, relative WFTs respect to selected transverse/longitudinal slopes and computed MTDs are presented.

According to the selected inputs (e.g. OMGWS, aircraft category, etc.) and selected transverse and longitudinal ranges the probability distribution of aircraft braking

distance simulated by the developed simulator code is presented in the following. The probability distribution of aircraft braking distance in violent rain condition with 100 mm/h rate of precipitation for transverse slopes 0.5 and 2.5% are presented in Figures 5(a) and 5(b) respectively.

In order to determine the impact of different slope values on the aircraft stopping location, two conditions are simulated; the aircraft landing on the runway without and with applying the double-pitched transverse slopes (1.5%). It is not possible to evaluate the *WFT* under the outer main

gear of aircraft in the condition of zero runway transverse grading, therefore, 0.1% is assigned. Previous boundary conditions (e.g. rain precipitation rate, OMGWS, etc.) are adopted in the process of this sensitivity analysis and the results are presented in Figure 6(a) and 6(b).

It can be interpreted from Table 3 and Figure 6 that transverse slope 1.5% is the optimum degree of steepness in decreasing the *WFT* under outer aircraft main gear tires while it does not compromise the manoeuvre capability of the aircraft.

This study is developed based on a finite element model (developed by the authors) that theoretically computes aircraft braking distance in wet pavement condition for different *WFT*s and an empirical model that evaluates the *WFT* for different transverse and longitudinal runway slopes (proposed by AASHTO). In order to validate the results achieved by this upgraded model, the optimum degree of transverse slope for safe ground manoeuvre should be compared to that recommended by existing regulations. According to FAA Advisory Circular 150/5300-13A (2012), for runway with approach categories of C, D and E, which means the aircraft touchdown speed can be ≥ 121 knots, the optimum transverse gradient that increase runway drainage capacity in order to have a safe wet-runway operation is between 1% and 1.5%. According to the same

Table 3. Relative *WFT*s respect to transverse/longitudinal slopes and *MTD*s

<i>WFT</i> under outer aircraft main gear tires ¹ [mm]			
Transverse slope ² [%]	<i>MTD</i> [mm]		
	0.5	1.0	1.5
0.5	4.22	4.09	3.83
1.5	2.49	2.23	1.88
2.5	1.92	1.61	1.23

Notes: ¹ Violent rain with 100 [mm/h] intensity is considered for the computations.
² Longitudinal profile is limited to 1[%] according to CS ADR-DSN (European Aviation Safety Agency, 2017).

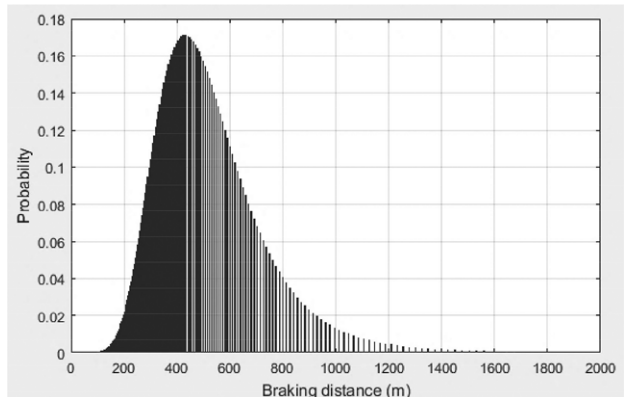
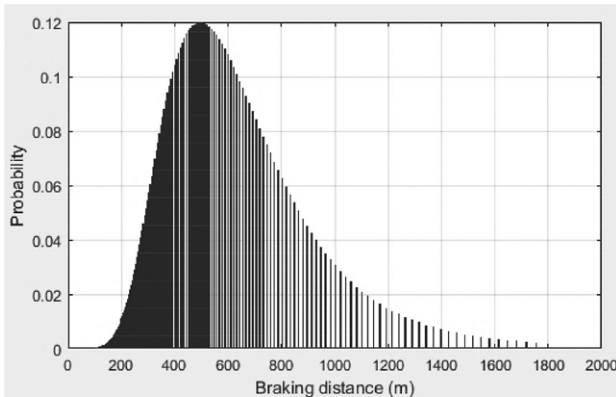


Figure 5. Simulated braking distance probability distribution in 100 mm/h violent rain and 1 mm *MTD* for transverse slopes of (a) 0.5%, and (b) 2.5%

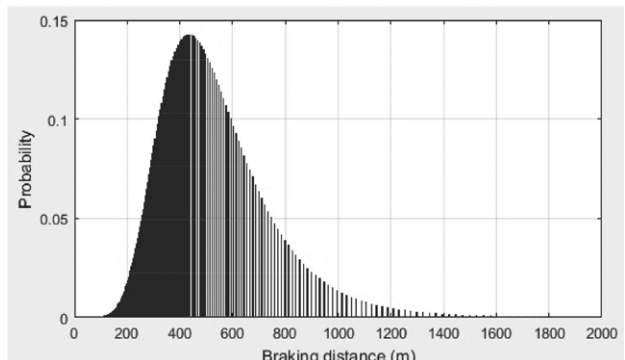
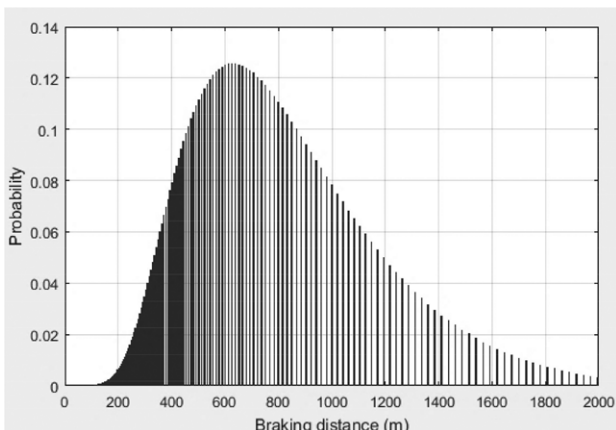


Figure 6. Simulated braking distance probability distribution in 100 mm/h violent rain and 1 mm *MTD* for (a) no transverse slope (0.1%), and (b) 1.5% transverse slope

specification, the optimum longitudinal gradient for runway with approach categories of C, D and E is 1% (FAA, 2012). By referring to these regulations, it is possible to validate the achieved result by Figures 5 and 6 that are demonstrating shorter aircraft braking distance in case of 1.5% runway transverse slope.

Conclusions

In order to evaluate the impact of longitudinal and transverse slopes on the probability of occurrence of landing excursion accidents in both wet and dry runway pavement conditions, a probabilistic risk analysis is developed. This framework is simulating the aircraft braking distances under selective boundary conditions of *WFT* on the runway, aircraft *MLW*, landing touchdown speed probability distributions, longitudinal/transverse slopes, and *MTD* of the pavement.

In order to simulate the flow mechanics of water-film on the sloped-surface runway, several studies have been carried out in the past decades, each of which has identified its own methodology. Among all, the corresponding formula, developed by American Association of State Highway and Transportation Officials (AASHTO), is implemented in this study. A wide spectrum of parameters (e.g. phase of flight, aerodynamic drag and uplift forces, headwind/tailwind, aircraft braking potential, reverse thrust, dry/wet runway, touchdown speed, etc.) are involved in simulation of aircraft braking distances and the consequent stoppage locations.

Parameters that affect the *WFT* existing on the runway pavement are surface *MTD*, the length of the resultant flow path (L_r), the resultant surface slope (S_r), and the rainfall intensity (I). L_r depends on the runway width (L_x), the transverse slope (S_x) and the longitudinal gradient (S_g). While the longitudinal gradient may significantly influence the flow path length, it does not appreciably affect the existing *WFT* on the runway.

FAARFIELD v1.42 software is adopted to compute the effective contact length (L_{cw}) between aircraft main gear tires and runway surface for each category of the selected aircrafts. L_{cw} is assigned to the runway width (L_x) in the computation of *WFT*. Based on the inputs and developed braking distance simulator code, the probability distribution of aircraft stopping location can be achieved.

Aircraft braking distance is simulated for runway transverse slopes of 0.5, 1.5 and 2.5%, and *MTD* of 0.5, 1 and 1.5 mm. According to the obtained results, 1% longitudinal and 1.5% transverse slopes are optimum degrees of steepness in decreasing the *WFT* under outer aircraft main gear tires while it does not compromise the maneuver capability of the aircraft. These suggested values cause optimum drainage capacity for the runway in landing and takeoff phases of flight. Furthermore, the peak of aircraft braking distance probability distribution can be shifted backward approximately 150 m in case of existence of 1.5% double-pitched transverse slopes respect to runway with no cross slopes.

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There is no conflict of interest to disclose.

Author contributions

MK collected, analyzed and interpreted the characteristics of critical aircraft that are adopted in the computations, moreover, developed the MATLAB-based script in order to simulate the aircraft braking distance. ET collected required initial inputs for the model and performed a comprehensive literature review on the topic and revised the manuscript. MC checked the model, revised the manuscript and managed all the required investigations for this study. All authors read and approved the final manuscript.

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