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Take-Off Analysis of Wide-Body Aircraft in Various Conditions by Integral Performance Method

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ABSTRACTS

The integral performance method is an alternative technique for estimating aircraft performance during take-off. This approach can be adaptable to various aircraft and take-off environmental conditions, and the calculations can be completed rapidly in a spreadsheet. This study takes the Boeing 747-400 aircraft, which has four engines, as an example to examine the impact of the aircraft and environmental factors on the necessary take-off distance for wide-bodied aircraft. Various All Engine Operative (AEO) and One Engine Inoperation (OEI) conditions are used to calculate the take-off distance. While OEI conditions include Continue Take-off (CTO) and Aborted Take-off (ATO), AEO conditions include normal conditions without rotation and normal conditions with rotation, the runway at an altitude of 3000 m, runway with a slope of 2^0 and 10 m/s headwind. The data used in this study include Boeing 747-400 aircraft characteristics such as wing configuration, engine performance, and environmental conditions. The analysis results show that altitude, runway slope, wind direction, and the percentage of thrusts used significantly affect take-off performance. Airport altitude contributes to aircraft performance, with higher altitudes requiring a longer take-off distance. The aircraft's take-off distance on a runway with a 2^0 slope is greater than the normal take-off distance on a flat runway. Thrust reduced to 90% of maximum thrust results in a longer take-off distance than maximum thrust. A 10 m/s headwind will provide a longer take-off distance than ordinary circumstances without wind. The magnitudes of the Balanced Field Length (BFL) and V_1 in the case of one engine inoperative (OEI) are 3200 meters and 85 meters per second, respectively.

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INTRODUCTION

Wide-bodied aircraft, such as long-range passenger or cargo aircraft, have special take-off requirements. Due to its size and weight, a long track is required for take-off [1]. The performance of aircraft take-off distance is critical in the aerospace sector to ensure flight safety and success. The performance of the take-off track length includes the distance required for the aircraft to reach take-off speed and lift itself off the runway [2].

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The take-off phase of a flight is the stage of flight in which an aircraft moves from the ground to take to the air [3]. The most essential phases of an aircraft's operation are take-off and landing. Considering that most aircraft crashes occur around that time. A lot of influencing factors, such as required speed, weather, weight, runway density, and many others [4]. As a result, a simulation or calculation is required to make it more convenient to analyze aircraft flight performance during take-off and anticipate any potential situation. Several studies were conducted to obtain accurate estimates based on the situation and conditions at the period of take-off. Pytka et al. created methods for calculating take-off performance on unpaved runways. In determining the required take-off distance, this method considers the distinctive properties of unpaved runways, such as surface resistance and stiffness [5]. Zhu et al. (2016) proposed an improved take-off performance calculation model that considers environmental factors like temperature, humidity, and air pressure. This model is intended to provide a more precise estimate of take-off performance under various environmental conditions [6]. Jia et al. and Melnichuk et al. created a commercial aircraft take-off performance calculation tool that accurately calculates aircraft data, environmental conditions, and airport design parameters to calculate the required take-off trajectory distance [7], [8]. Ghazi et al. research to optimize take-off performance by considering environmental factors and reducing the environmental impact. The optimization method is used to find parameters that generate energy-efficient take-off performance while lowering emissions [9].

An integral performance method is a different approach that can be used to estimate aircraft performance during take-off. This approach has the benefit of being resilient to a variety of aircraft and take-off environmental conditions, and the calculations can be completed promptly in a spreadsheet.

With the assistance of the integral performance method and the four-engine Boeing 747-400 aircraft as an example, this study seeks to understand how aircraft and environmental factors affect the required take-off distance for wide-bodied aircraft. Different All Engine Operative (AEO) and One Engine Inoperation (OEI) conditions are used to calculate the take-off distance. AEO conditions include normal without rotation, normal with rotation, runway at 3000 m, runway with a slope of 2^0, 90% thrust reduction, and 10 m/s headwind, while OEI conditions include Continue Take-off (CTO) and Aborted Take-off (ATO).

METHODS

The Boeing 747-400 is a model of wide-bodied aircraft. The Jumbo Jet is the name of the aircraft, which has a capacity of 400–600 passengers. The Boeing 747 is able to travel a maximum distance of 13,570 km between continents and can fly at high speeds (typically 0.85 Mach, or 909 km/h). The largest number of aircraft operated by an Indonesian airline at the time was the Boeing 747-400. This aircraft's aerodynamic and engine performance data are readily available, making it simpler to determine take-off performance.

The forces acting on the aircraft during take-off

The force of gravity, aerodynamic forces (lift and drag), propulsion forces (thrust), and frictional forces between the wheels and the runway are the various forces acting on the aircraft during take-off [3]. **Figure 1** illustrates an overview of the forces acting on the aircraft during take-off.

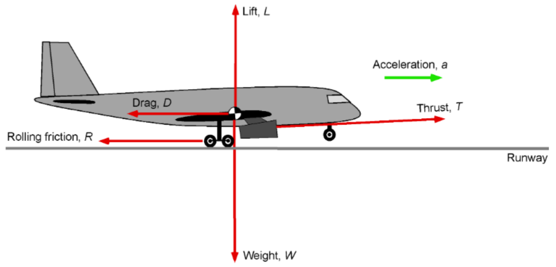

Figure 1. The forces acting on the aircraft during take-off [3].

Lift

Lift is the upward force acting perpendicular to the relative wind direction on a wing. Lift is produced by the dynamic effect of air performing on the wing and acting perpendicular to the direction of flight through the center of lift of the wing to counteract the force of weight. The lift can be adjusted by moving the steering wheel forward or backward, which changes the angle of attack [10]. When the angle of attack increases, the lift increases (assuming all other factors remain constant). While the aircraft reaches its maximum angle of attack, the lift disappears rapidly, referred to as the stalling angle of attack or the burble point. Lift and drag are also affected by the density of the air. Several factors influence air density, which includes pressure, temperature, and humidity. The lift coefficient is a dimensionless parameter that describes the magnitude of the lift force acting on an object moving through a fluid [11]. The lift generated by the wing is denoted as follows:

$$L = \frac{1}{2}\rho V^2 S C_L \quad (1)$$

Where, L = lift, V = velocity; S = reference area; C_L = coefficient of lift

Wing flaps determine lift performance during take-off. The flap increases the coefficient of lift, which allows it to maintain lift at low speeds (take-off and landing). The flap's principle of operation for increasing C_L is to increase the mean camber of the airfoil wing. The flaps also slow down the stalling process and can be interpreted as a shorter ground run, but it will not reduce the 50 ft take-off any further because the flaps will reduce the rate of climb. **Table 1** shows several types of flaps.

Table 1. $C_L\,(max)/cos\Lambda$ values for various types of flaps [11].

High Lift Device		Typical Flap Angle		$(C_L)_{Max}/cos\wedge$	
Trailing-Edge	Leading Edge	Take - Off	Landing	Take - Off	Landing
Plain Flap		20^0	60^0	1.4–1.6	1.7–2.0
Single – Slotted Flap		20^0	40^0	1.5–1.7	1.8–2.2
Fowler – Flap					
Single – Slotted		15^0	40^0	2.0–2.2	2.5–2.9
Double – Slotted		20^0	50^0	1.7–1.95	2.3–2.7
Double – Slotted	Slat	20^0	50^0	2.3–2.6	2.8–3.2
Triple - Sloted	Slat	20^0	40^0	2.4–2.7	3.2–3.5

Drag

Drag is the force that drives objects backward as a consequence of airflow obstruction caused by wings, fuselage, and other objects. Drag is the opposite of thrust. There are two types of drag in flight: parasite drag and induced drag. Site drag is classified into two types: Form drag is caused by disruptions in the airflow passing through the fuselage. Skin friction occurs by friction with the aircraft's surface. Form drag is the less difficult of the two types of parasite drag to reduce when designing aircraft. In particular, the smaller the aircraft's streamlined shape, the less parasite drag it will have. Meanwhile, the most challenging type of parasite drag to reduce is skin friction. It is impossible to manufacture perfectly smooth aircraft surfaces in the aircraft manufacturing industry. Rough surfaces may trigger streamlined airflow to be diverted across the surface. Induced drag occurs as a result of the work of the wings that generate lift. Aircraft wings use the energy from the free flow of air to generate lift. When the lift is generated, the pressure beneath the wing surface is greater than the pressure above the wing surface. As a result, air will flow from the low-pressure area above the wing to the high-pressure area underneath the wing. The stresses that occur in the area around the tip of the wing tend to be balanced and produce a lateral flow outward from the underside of the wing toward the top of the wing. This downward airflow can deflect the lift vector backward, parallel to the air direction (relative wind), which leads to induced drag. In any case, if the aircraft speed is low and the required angle of attack is greater to generate lift equal to the aircraft's weight, the induced drag will be higher [2]. The wing's drag is expressed as follows:

$$D = \frac{1}{2}\rho V^2 S C_D \qquad (2)$$

Where, L = lift, V = velocity; S = reference area; C_D = coefficient of drag

Drag Polar is the relationship between lift and drag on an airplane as the angle of attack changes, polar drag is expressed in the relationship between the drag coefficient and the lift coefficient [12].

$$C_D = C_{D0} + C_{Di} = C_{D0} + \frac{{C_L}^2}{\pi A e} = C_{D0} + k{C_L}^2 \qquad (3)$$

with C_{D0} = zero lift drag coefficient; C_{Di} = induced drag coefficient; k = lift-induced drag coefficient factor; e = the Oswald factor (0.70-0.90); A = aspect ratio of the wing.

Weight

The combined weight of the aircraft's payload, the crew, fuel, and cargo or baggage is referred to as weight. The weight acts vertically downward through the aircraft's center of gravity, driving the plane down against lift. The center of gravity is defined as the point at which all of the aircraft's weight is concentrated and affects the aircraft's stability. If the aircraft is held precisely at the center of gravity, it will balance in any attitude. Weight and lift have a relationship. Lift is required to compensate for the aircraft's weight, caused by gravity acting on the aircraft's mass. The weight acts downward through the plane's center of gravity. The aircraft will not lose altitude when the lift is equal to the weight in a flat and stable flight. However, if the lift is less than the weight, the plane loses altitude; if the lift is more significant, the plane gains altitude [13].

Thrust

Thrust is the force produced by aircraft engines, which can be turbofans, turboprops, or piston engines. Trust is the exact opposite of the drag force. Thrust is used before the aircraft starts moving. If the engine power is reduced in level flight, the thrust will be less than the drag, resulting in the aircraft slowing down. As long as the thrust is greater than the drag, the plane will continue to slow down until its speed is no longer sufficient to keep the aircraft in the air. If the engine power is increased, the thrust will be greater than the drag, causing the aircraft to accelerate. However, if the thrust equals the drag, the aircraft will fly at a constant speed. If the thrust is reduced and the aircraft's velocity is reduced, the lift will be less than the weight, and the plane will begin to fall from its height. In this case, you can add the angle of attack to generate lift equal to the weight, allowing the plane to maintain its altitude [8].

Boeing 747-400 aircraft specifications

The Boeing 747-400 is a large passenger aircraft powered by four turbofan engines that can reach a maximum speed of 988 km/h. The Boeing 747-400 aircraft is depicted in **Figure 2,** and detailed specifications are in Table 2. Specifications of Boeing 747-400 Aircraft[1].**Table 2.**

Table 2. Specifications of Boeing 747-400 Aircraft[1].

Parameter	Value
Wing Area (S)	525 m^2
MAC (c)	8.32 m
Span (b)	64.4 m
Aspect ratio	7.7
Wing sweep angle	37.5^0
Length	68.6 m
Hight	19.4 m
Weight MTOW	396893 kg
Wing Type	Triple – Sloted Fowler Flaps
Number of engines	4
Thrust maximum	1008000 N (All Engine)

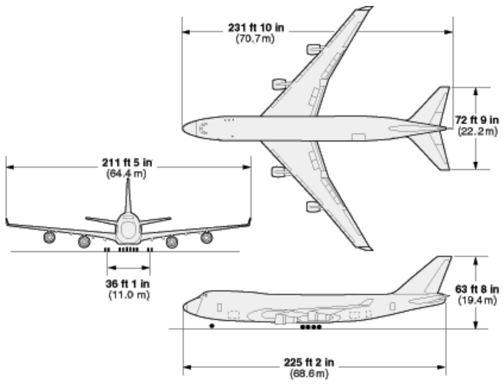

Figure 2. Boeing 747-400 basic geometry [1].

Aerodynamics and Propulsion Data

The 747 aircraft is equipped with Triple – Sloted Fowler Flaps. Based on Table 1, the Flap deflection at the Take–Off Position with a flap of 20^0 is $C_L(max)/cos\Lambda=2.6$; with Λ = sweep angle (37.5^0) dan S= 525 m^2.

$$C_L(max)/cos\ 37.5^0 = 2.6 \quad (4)$$

$$C_L(max) = 2.162$$

To get the C_L value in the take-off condition, which is 0.991, extrapolation was carried out from the C_L curve to the angle of attack in cruising flight conditions (clean configuration), and the result is shown in **Figure 3**.

While the drag coefficient (C_D) at take-off is calculated using the polar drag equation with C_{D0} = 0.075 and a lift-induced drag coefficient k = 0.045, the C_D at take-off is 0.121. The Boeing 747-400 aircraft's aerodynamic data were obtained from the Boeing 747-400 Operation Procedure Manual [12]. The manual operation provides propulsion data, namely maximum thrust at 0 m/s and Thrust at Climbing speed (V_{climb} = 98.3 m/s). The data is then extrapolated based on the velocity function to obtain thrust, as shown in **Table 3**. During take-off, the fuel consumption is 11400 kg/hour (3.7 kg/s).

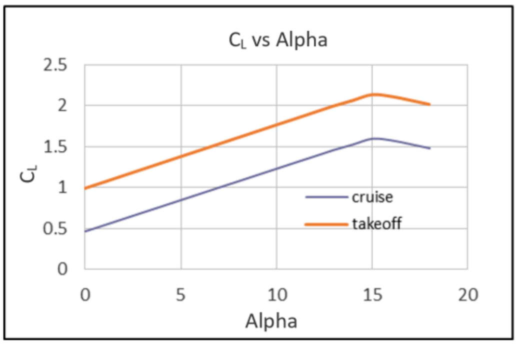

Figure 3. The C_L graph is plotted against the angle of attack.

Table 3. Trust data to velocity [14].

V-tas		Thrust
knot	m/s	N
0	0	1008000
20	10.3	997445
40	20.6	986890
60	30.9	976335
80	41.2	965781
100	51.4	955226
120	61.7	944671
140	72.0	934116
160	82.3	923561
180	92.6	913006
191	98.3	907200

Take-off Performance Calculation Method by Integral Performance Method in Spreadsheet

This spreadsheet's Take-off Distance Calculation Method with the Integral Performance Method was derived from Boeing's Take-off Performance Handout [15]. A table for calculating aircraft take-off performance is provided in **Table 4**.

Table 4. Spreadsheet calculating aircraft take-off performance.

t	V-GS	V-TAS	q	m	W	T	C_L	C_D	L	D	$\emptyset$	μ	a_x	a_z	V_x	V_z	x	z	V	γ	θ	α
(s)	m/s	m/s	Pa	kg	N	N			N	N			m/s^2	m/s^2	m/s	m/s	m	m	m/s	deg	deg	deg
0																						
1																						
2																						
3																						
4																						
…																						

The acceleration is calculated at 0 seconds using Newton's second law of motion, which states that the amount of force acting equals the mass multiplied by the acceleration.

$$\sum F = ma \quad (5)$$

$$Thrust - Drag - Friction - F_{slope} = ma \quad (6)$$

$$T - D - \mu(W - L) - W\phi = \frac{W}{g}a \quad (7)$$

$$a = \frac{W}{g}[T - \mu W - (C_D - \mu C_L)qS - W\phi] \quad (8)$$

Velocity and distance calculated by.

$$V_x = a_x(t_{now} - t_{previous}) + V_x\ previous; \quad (9)$$

$$x = V_x(t_{now} - t_{previous}) + x\ previous \quad (10)$$

$$V_z = a_z(t_{now} - t_{previous}) + V_z\ previous \quad (11)$$

$$z = V_z(t_{now} - t_{previous}) + z\ previous \quad (12)$$

where,

W = weight
T = Thrust
V_x = horizontal velocity
V_z = vertical velocity
V = V-GS = ground speed
V-TAS = air speed
x = ground distance
z = high distance
a_x= horizontal acceleration
$a_z = (L - W)/m$ = vertical acceleration
ϕ = runway slope
μ = runway friction coefficient
q = dynamic pressure
θ = pitch angle
γ = climb angle
α = θ - γ = angle of attack

Take-off performance is calculated and analyzed with all aircraft engines operational / All Engine Operative (AEO) and one engine inoperative / One Engine Inoperative (OEI). It is estimated in various conditions for All Engine Operative (AEO) conditions, including normal conditions without rotation, normal conditions with rotation, the runway at an altitude of 3000 m, runway with a slope of 20, 90% thrust reduction, and the presence of a headwind of 10 m/s. Meanwhile, for One Engine Inoperative (OEI), take-off performance is calculated when the engine is not operating at engine failure V_{ef} speeds of 60 m/s, 70 m/s, 80 m/s, and 90 m/s with Continued Take-Off (CTO) conditions. While the engine begins to shut down, CTO and ATO thrust reduction is calculated using Boeing's Spindown Factor Throttle Chop [3]. **Figure 4** also shows a graph of decreasing thrust when the engine is not operating.

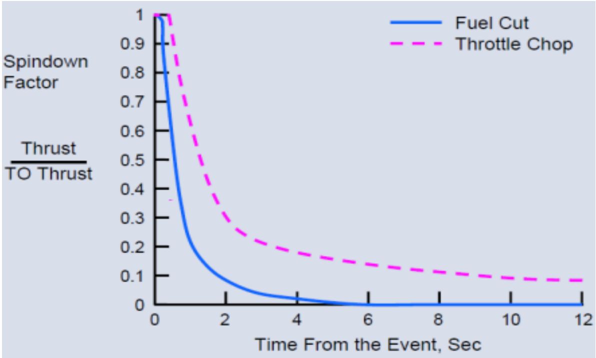

Figure 4. Thrust reduction graph when the engine is not operating [14].

RESULTS AND DISCUSSION

All Engine Operative

Normal Take-Off without Rotation

A normal take-off is modeled at sea level altitude with a flap deflection of 20^0, C_L 0.991, and C_D 0.121. According to the calculation results, the aircraft began to lift (lift-off) at the 62nd second and a distance of 3968 m. The aircraft then lifted to pass the obstacle height of 50 ft (15.24 m) after 4776 m and 69 seconds. This distance differs from the 3033 m [14] specified in the Boeing 747-400 Operation Manual for normal take-off conditions. This difference is due to the aircraft not being rotated.

Normal Take-Off with Rotation

The aircraft rotates by 2 degrees every second under normal take-off conditions with rotation, with a CL increment of 0.0768 and a CD increment of 0.0035 for each one-degree increment. The aircraft begins to rotate at Vr = 92.97 m/s. According to the calculations, the plane starts to lift (lift off) at a distance of 2418 m in the 50th second. The aircraft then rose to a height of 50 feet (15.24 meters) after a distance of 3004 meters and 53 seconds. This distance correlates to the take-off distance specified in the Boeing 747-400 Operation Manual, which is 3033 m [14]. **Figure 5** and **Table 5** show more information about the difference between take-off distance without and with rotation.

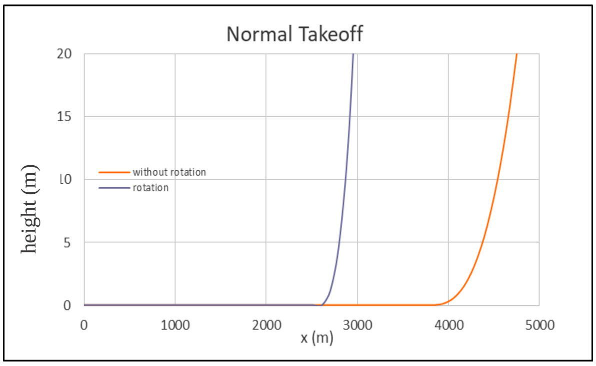

Figure 5. Take-off distance under normal conditions.

Table 5. Take-off performance under normal conditions.

Case	Time	X_{LO}	Time	X_{TO}	V_{TO}
	s	m	s	m	m/s
Without rotation	62	3968	69	4776	118
Rotation	50	2706	53	3004	100
Reference				3033	

Take-off at a runway altitude of 3000 meters.

The air density decreases from 1.225 kg/m3 to 0.90926 kg/m3 at 3000 meters. This decrease causes a decrease in dynamic pressure, which causes the thrust and lift values to decrease. In addition to density, increasing altitude reduces static pressure and air temperature, which reduces the compression performance of the aircraft engine, resulting in decreased thrust and a longer take-off distance. **Figure 6** depicts the results of the take-off calculation at a runway altitude of 3000 m; the aircraft begins to lift at a distance of 2885 meters and 51 seconds. The aircraft climbs to 50 feet (15.24 meters) after 3168 meters and 54 seconds. At sea level, it becomes longer than normal take-off conditions.

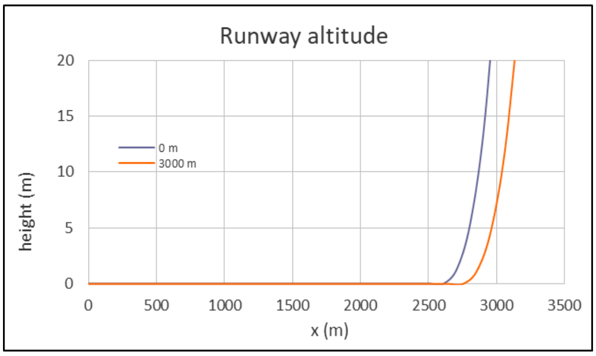

Figure 6. Take-off distance at runway altitude of 3000 meters.

Take-off on the 2^0 runway slope

An airstrip with a positive slope (up) requires more thrust to lift the aircraft. As a result, the distance required for the aircraft to take off increases. According to the take-off calculation at the 20th runway slope, the aircraft lifted to a height of 50 ft (15.24 m) at 3461 m and 64 seconds, which is longer than the normal take-off distance at a runway slope of 0^0. The results are shown in **Figure 7**.

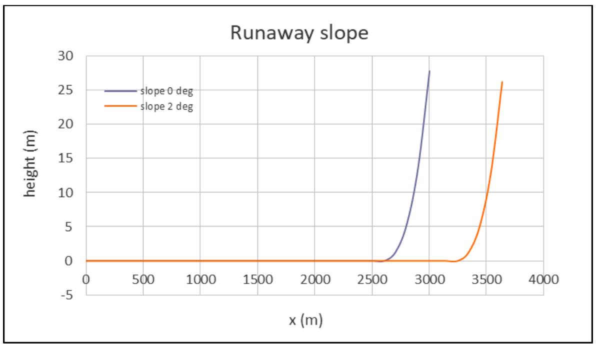

Figure 7. The take-off distance on the 2^0 runway slope.

Take-off with 90% Thrust of Maximum Thrust

Reducing thrust from the maximum value has several benefits, including increased engine life, reduced engine breakdown, and lower engine maintenance costs. However, the reduction will result in a longer distance required for the aircraft to take off (as shown in **Figure 8**).

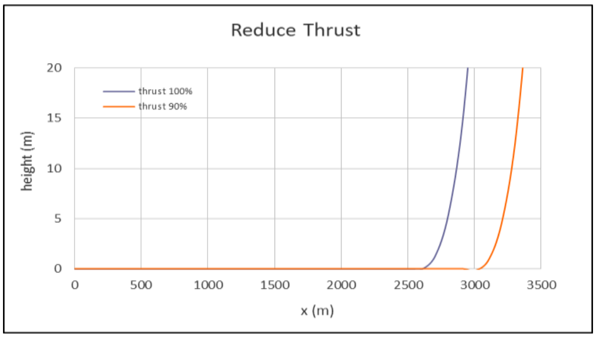

Figure 8. Take-off distance with 90% thrust of maximum thrust.

Take-off with a 10 m/s headwind

The presence of a headwind increases the aircraft's actual velocity against the wind. As a result, the aircraft will take off faster and travel a shorter distance than under normal take-off conditions. **Figure 9** depicts the take-off distance in a 10 m/s headwind. The take-off distance was reduced from 3004 m to 2900 m.

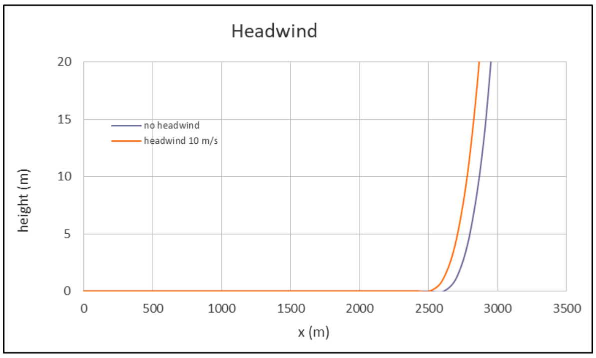

Figure 9. Take-off distance with Headwind 10 m/s.

One Engine Inoperation (OEI)

Continued Take-off (CTO)

As its driving force, the Boeing 747-400 aircraft is outfitted with four engines. The thrust is equal to the sum of the thrust of the three operating engines plus the thrust of the one engine not operating multiplied by the spindown factor of thrust in the case of continued take-off with an engine not operating. **Figure 10** illustrates the take-off distance when one engine is not running at full power. It can be seen that when one of the engines fails, the distance for the aircraft to take off increases. The engine shuts down at the lowest V_{ef} speed, corresponding to the longest take-off distance. The closer the rotational speed V_r is to V_{ef}, the closer the take-off distance will be to the normal take-off distance.

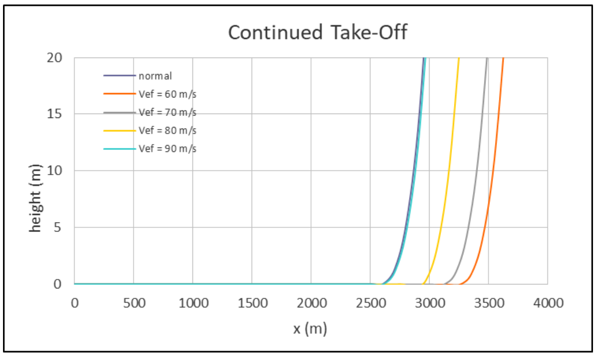

Figure 10. Continued take-off, one engine inoperative.

Aborted Take-Off (ATO)

All engines are turned off when a take-off is aborted and the engine fails to operate. The following phases were completed during the ATO: brake on, throttle chop, and spoiler up. When the engine is turned off, the brakes are immediately applied; the coefficient of friction during braking is 0.35. The engine then begins to turn off one to two seconds after braking by closing the throttle; during this phase, there is a significant decrease in thrust based on the time function. After the throttle has been cut, the spoiler begins to be raised to increase braking until the plane comes to a stop. When the spoiler is raised, the C_L and C_D are -0.25 and 0.1427, respectively.

While the engine is turned off, the take-off distance in the case of a continuous take-off and the distance of the aircraft to stop in the case of an aborted take-off are graphed. The intersection distance between ATO and CTO is the Balanced Field Length (BFL), or total distance from the runway (including stopway and clearway). While the intersection speed between CTO and ATO is V1, pilots commonly use it to determine whether the aircraft should continue to take-off or abort it. **Figure 11** depicts the take-off and braking distances in the OEI case as a function of engine failure speed. BFL and V_1 have magnitudes of 3200 meters and 85 meters per second, respectively. This V_1 has a magnitude different from the Boeing 747-400 manual operation, which is 78 m/s. This difference in V_1 speed is due to the calculation, which shows that the rotational speed V_r = 92.9 m/s is greater than the reference speed of 87.9 m/s (Dees, 2000). This rotation speed delay is used to obtain a close-to-reference take-off distance value.

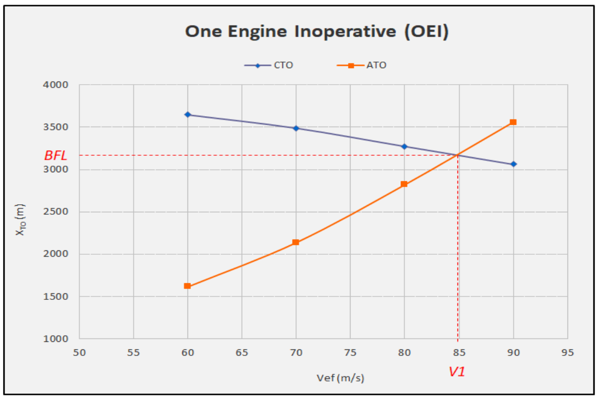

Figure 11. BFL and V_1 in the case of one engine inoperative.

CONCLUSION

Based on the results of the take-off calculations, it could be justified to conclude that the normal take-off distance is 4776 m without rotation and 3004 m with rotation. The aircraft's take-off distance on the runway at 3000 m is greater than the normal take-off distance at 0 m.The take-off distance for an aircraft on a runway with a slope of 2^0 is greater than the normal take-off distance on a flat runway. When thrust is reduced to 90% of maximum thrust, the take-off distance is longer than when maximum thrust is used. A 10 m/s headwind will result in a longer take-off distance than normal conditions without wind. The magnitude of the Balanced Field Length (BFL) and V_1 in the case of a single engine in operation (OEI) is 3200 meters and 85 meters per second, respectively. Calculating the take-off distance in this spreadsheet using the integral performance method is adequate for analyzing aircraft performance during take-off.

Author Contributions

The first and second authors have contributed equally to this work. The third and fourth author has contributed to collecting aerodynamics data, translating and checking the language.

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