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Effect of Paving Runway and Atmospheric Conditions on Airplane Takeoff Distance and Time

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ABSTRACT

This paper study the effect of paving runway and atmospheric conditions on airplane takeoff distance and time with roll stage and air stage. Two airplane types DC-9 and Boeing 747-400 were considered for different atmospheric condition with different weight by using time step integration technique and Krenkel and Salzman assumed that the variation of thrust and velocity create the balance of forces equations on the aircraft during its takeoff run. The air temperature and airplane weight and runway paving are the most effected parameters on takeoff time and distance. The runway paving consideration are very important for airport design and runway construction to minimums fuel consumption during takeoff.

1. Introduction

Paving is main construction design for runway. The integral point of view of the runway paving depend on specific airport and the expected traffic which can be handle. Many studies on runway paving being down such as noise load bearing, cost, maintenance and economical (airplane fuel consumption) which is the most important view for a huge number of takeoff and landing airplane. this studies depend on the aerodynamic analysis such as the four balance forces, speed, friction, performance coefficient and atmospheric condition for each type of airplane within FRA rules.

2.Theoritical Analysis

2.1 Forces Acting During the Ground Stage

The takeoff consist of two stage ground distance and air distance which also consist of two part transition and climb distance ,the ground distance start from brake of unit reaches the takeoff velocity (V_{TO})and the takeoff distance started from takeoff distance until the airplane reaches 35 ft [1]. The ground stage is noted by distance (S_1). Takeoff distance noted by (S_2) [2].as shown in figure (1)[3].

Lift, weight, thrust, and drag acting force on the airplane during the takeoff in addition to usual forces, and during rolling distance the airplane effected by bearing friction, brake drag [4]. This force reduces as lift increase and the force on wheels is reduced [5]. This force is given by [6]:

$$R = \mu(W - L) \quad (1)$$

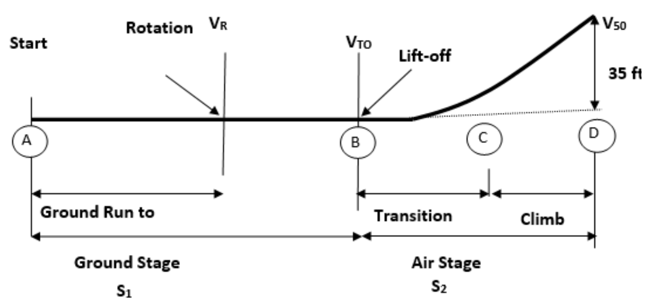

Figure (1) Take off Path

The combination of force in figure (1) assumes engine thrust is parallel to the runway. For airplane with engines amounted at the angle, horizontal component of thrust is not reducing significantly until the angle becomes quite large. The normal component of thrust generated by engine balance weight component. The mass of the airplane, however, must be computed using the actual airplane weight [7].

Since the work done equal to change in energy produces [7]:

$$\int_0^{S_1} [T - D - \mu(W - L)]ds = \frac{W}{2g}(V^2{}_{TO}) \quad (2)$$

Table (1) Coefficient of Friction Value [6]

Surface	Typical Values of coefficient of friction (μ)	
	Rolling Brake off Ground Resistance Coefficient	Brakes on wheel braking coefficient
Dry concrete/Asphalt	0.02-0.05	0.3-0. 5
Wet concrete/Asphalt	0.05	0.15-0.3
Icy concrete/Asphalt	0.02	0.06-0.1
Hard Turf	0.05	0.4
Firm Dirt	0.04	0.3
Soft Turf	0.07	0.2
Wet Grass	0.08	0.2

The expression can be evaluated assuming the entire remains constant at some value. simplified and solving equation (2) gives [7]

$$[T - D - \mu(W - L)ds]_{Avg} S_1 = \frac{1}{2}\frac{W}{g}(V^2{}_{TO}) \quad (3)$$

Solving for S_1

$$S_1 = \frac{WV^2{}_{TO}}{2g[T - D - \mu(W - L)ds]_{Avg}} \quad (4)$$

2.2 Forces Acting During the Air Stage

The Equation for air distance can be solve similar to the ground distance equation except the resistance force which equal to zero [8]:

$$\int_{Liftoff}^{35\,ft} [T - D]ds = \frac{W}{2g}(V^2{}_{35} - V^2{}_{TO}) + 35W \quad (5)$$

Assuming this quantity remains constant at some average value, the integration of Equation (5) becomes [8]:

$$S_2 = \frac{W\left(\left(\frac{V^2{}_{35} - V^2{}_{TO}}{2g}\right) + 35\ \right)}{[T - D]_{Avg}} \quad (6)$$

To minimize the value of S_2 for a given weight, a constant speed climb is conducted at maximum excess thrust, while maximum excess thrust occur at speed for minimum drag$\frac{L}{D}\Big]_{max}$ [9].

2.3 Takeoff Correction

Wind Correction

Ground speed represent the velocity at lift off. Since ground speed and true speed are equal in zero wind condition, the ground speed required with wind, V_{TO_W}[10]

$$V_{TO_W} = V_{TO} - V_W \tag{7}$$

V_W Is positive for a head wind and includes only the component of wind velocity parallel to the takeoff direction from equation (4) and equation (6) [10]:

$$S_{1_W} = \frac{WV^2{}_{TO}}{2gT_{ex_{avg_W}}} \tag{8}$$

The subscript, W, indicate a parameter in the wind environment. Substituting Equation (7) into equation (8) [10]:

$$S_{1_W} = \frac{W(V_{TOw} + V_w)^2}{2gT_{ex_{Avg_W}}} \tag{9}$$

Dividing equation (9) by equation (8) and rearranging gives:

$$S_{1_{Std}} = S_{1_W}\frac{T_{ex_{Avg_W}}}{T_{ex_{Avg}}}\left(1 + \frac{V_W}{V_{TO_W}}\right)^2 \tag{10}$$

The different in excess thrust due to wind is difficult to determine but is does have a significant effect on takeoff roll. Then for steady state winds equation for the correction head wind /tail wind component [10]:

$$S_{1_{Std}} = S_{1_W}\left(1 + \frac{V_W}{V_{TO_W}}\right)^{1.85} \tag{11}$$

For the air stage

$$S_{2_{Std}} = S_{2_W} - \Delta S_2 \tag{12}$$

Runway Slope

The runway slope can be adding to equation (3) to gives [11].

$$T_{ex_{Avg}}S_{1_{SL}} = \frac{1}{2}\frac{W}{g}V^2{}_{TO} - WS_{1_{SL}}sin\theta \tag{13}$$

The subscript SL indicates a runway slope parameter.

Solve for $S_{1_{SL}}$[11]

$$S_{1_{SL}} = \frac{WV^2{}_{TO}}{2g\left(T_{ex_{Avg}} + Wsin\theta\right)} \tag{14}$$

Solving equation (4) and equation (14) for average excess thrust, equating the results, and solving for S_1produces an expression for a standard S_1[10]

$$S_{1_{Std}} = \frac{S_{1_{SL}}}{\left(1 - \frac{2gS_{1_{SL}}}{V^2{}_{TO}}sin\theta\right)} \tag{15}$$

2.4 Thrust, weight, and Density

The density has great effect on engine parameters specially thrust which change the airspeed required to fly at specific lift and weight but it's difficult to expression formula for this relationship, but empirical formula may be provide [10].

Ground stage

$$S_{1_{Std}} = S_{1_{Test}}\left(\frac{W_{Std}}{W_{Test}}\right)^{2.3}\frac{\sigma_{Test}}{\sigma_{Std}}\left(\frac{T_{N_{Test}}}{T_{N_{Std}}}\right)^{1.3} \tag{16}$$

Air stage

$$S_{2_{Std}} = S_{2_{Test}} \left(\frac{W_{Std}}{W_{Test}}\right)^{2.3} (\frac{\sigma_{Test}}{\sigma_{Std}})^{0.7} (\frac{T_{N_{Test}}}{T_{N_{Std}}})^{1.6} \quad (17)$$

3.Results and Discussion

All discussion bases on normal condition, concert paving martial and 15 c^0 weather temperature and sea level runway height. All results tabulated in table (2) and table (3).

Runway paving marital, hard truff, dry grass and long grass increases total take off distance by 9%,14% and frequently and total take off time by 6%, 10% 31%for 747-400 airplane (fig (2)) and for DC-9 airplane the take-off distance increases by 55,8%, and 26% and take off time by 5%,155 and 58%55% (fig (3)). It is not recommended to have takeoff through runway paved with soft and short grass.

Temperature condition effects shown in fig (8) and fig (9) for 747-400 airplane and DC-9 airplane gives same effect 20% approximately increases in lift off and total take of distance.

Airplane weight effect the total take off distance increases as airplane weight increase, for 747-400 airplane the total takeoff distance increases by 30% and for DC-9 total take off distance increases by 20% approximately, fig (4) and fig (5).

Runway height also increases the total take off distance as the runway level increases and that increase by 10% for both airplane type, fig (6) and fig (7).

4.Conclusion

1. Runway paving material was the most parameter affected about 25% approximately and it is not recommended to have takeoff through runway paved with soft and short grass
2. Each one ton increases the takeoff distance 20% approximately.
3. Temperature between 15c^0 -60 c^0 increases take off distance 20% approximately.
4. Runway height increases 1000 ft the takeoff distance by 10% proximately.

5.Nomenclature

D	Drag	N
g	Gravitational acceleration	ft./sec2
L	Lift	N
S_1	Takeoff distance, Brake off to Lift off	ft.
S_2	Takeoff distance, Lift off to 35 ft.	ft.
$S_{1_{std}}$	Standard Takeoff distance, Brake off to Lift off	ft.
$S_{1_{SL}}$	Takeoff distance, Brake off to Lift off ,Sloping runway	ft.

S_1	Takeoff distance, Brake off to Lift off	ft.
S_{1_W}	Takeoff distance, Brake off to Lift off, with respect to wind	ft.
$S_{1_{Test}}$	Test Takeoff distance, Brake off to Lift off	ft.
$S_{1_{Std}}$	Standard Takeoff distance, Brake off to Lift off, with respect to wind	ft.
ΔS_2	Average Takeoff distance, Lift off to 35 ft.	ft.
T	Thrust	N
$T_{ex_{avg_W}}$	Average Excess Thrust, with respect to wind	N
$T_{ex_{avg}}$	Average Excess Thrust	N
$T_{N_{Test}}$	Test Net Thrust	N
$T_{N_{Std}}$	Standard Net Thrust	N
$T_{ex_{Aveg}}$	Average Excess Thrust	N
$T_{ex_{Aveg_W}}$	Average Excess Thrust with Respect to Wind	N
V_{TO}	Takeoff Ground Speed	ft./sec
V_{TO_W}	Takeoff Ground Speed with Respect to Wind	ft./sec
W_{Std}	Standard Weight	N
$W_{\_Test}$	Test Weight	N
θ	Runway Angle	Deg
$\sigma_{\_Test}$	Test Density	------
$\sigma_{\_Std}$	Standard Density Ratio	--------
μ	Coefficient of Fraction	------

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Table (1):-Airplane 747-400 data

Airplane 747-400			Rotation Velocity ft/sec	Lift off velocity ft/sec	Velocity over obs ft/sec	Rotation Distance ft	Lift off Distance ft	Distance to obst ft	Rotation Time sec	Lift off Time	Time to obst sec	Total Distance ft	T T s
	Runway Material Construction	Dry Concert	266.015	278.529	285.150	6678.896	7495.849	8175.245	46.140	49.140	51.548	8175.245	51.548
		Hard Truff	266.015	277.285	284.134	7423.956	8239.011	8927.846	51.173	54.173	56.623	8927.846	56.623
		Dry Grass	266.015	276.660	283.611	7862.404	8676.513	9369.403	54.125	57.125	59.595	9369.404	59.595
		Long Grass	266.015	273.515	281.083	11160.320	11969.66	12688.240	76.100	76.100	81.688	12688.240	81.688
		Soft Ground	266.015	267.109	276.142	71778.380	72578.06	73358.480	435.917	435.91	441.78	73358.480	441.785
	Temperature	-5 C^0	256.624	268.949	275.569	6329.494	7117.988	7775.749	45.374	48.374	50.787	7775.749	50.787
		15 C^0	266.015	278.219	284.959	6851.105	7667.585	8352.451	47.304	50.304	52.733	8352.451	52.733
		35C^0	275.091	287.180	294.012	7377.911	8221.439	8931.788	49.187	52.187	54.628	8931.788	54.628
		+60 C^0	285.031	296.998	304.021	7981.281	8854.443	9598.279	51.269	54.269	56.741	9598.279	56.741
	Runway Height	_1000 ft	262.222	274.474	281.376	6637.665	7442.840	8126.982	46.522	49.522	51.982	8126.982	52.733
		0 ft	266.015	278.219	284.959	6851.105	7667.585	8352.451	47.304	50.304	52.733	8352.451	51.982
		+1000 ft	269.887	282.042	288.775	7072.760	7900.781	8594.078	48.104	51.104	53.531	8594.078	53.531
	Airplane Weight	697200 lb	264.127	276.615	283.406	6620.587	7431.835	8105.096	46.092	49.092	51.494	8105.096	
		707200 lb	266.015	278.219	284.959	6851.105	7667.585	8352.451	47.304	50.304	52.733	8352.451	
		717200 lb	267.889	279.817	286.651	7086.586	7908.269	8612.219	48.533	51.533	54.016	8612.219	

Table (1):-Airplane Dc-9 data

			Rotation Velocity ft/sec	Lift off velocity ft/sec	Velocity over obs ft/sec	Rotation Distance ft	Lift off Distance ft	Distance to obst ft	Rotation Time sec	Lift off Time	Time to obst sec	Total Take off Distance ft	T
Airplane DC-9	Runway Material Construction	Dry Concert	219.912	242.456	256.604	2813.535	3507.355	4205.914	24.517	27.517	30.310	4205.914	
		Hard Truff	219.912	240.947	255.652	3018.629	3710.150	4423.370	26.283	29.283	32.149	4423.370	
		Dry Grass	219.912	240.191	255.176	3132.642	3823.012	4543.619	27.265	30.265	33.168	4543.619	
		Long Grass	219.912	236.390	252.965	3861.834	4546.425	5309.650	33.529	36.529	39.640	5309.650	
		Soft Ground	219.912	220.864	247.871	58612.290	59273.450	60333.340	446.515	446.515	454.015	60333.340	
	Temperature	-5 C^0	212.148	234.345	248.129	2658.414	3328.421	3996.268	24.017	27.017	29.780	3996.268	
		15 C^0	219.912	242.079	256.354	2862.196	3555.441	4257.273	24.936	27.936	30.746	4257.273	
		35C^0	227.415	249.557	264.299	3066.570	3782.277	4517.720	25.825	28.825	31.682	4517.720	
		+60 C^0	235.632	257.747	272.974	3298.523	4038.831	4811.183	26.801	29.801	32.706	4811.183	
	Runway Height	_1000 ft	216.776	238.955	253.054	2779.001	3462.861	4151.553	24.564	27.564	30.358	4151.553	
		0 ft	219.912	242.079	256.354	2862.196	3555.441	4257.273	24.936	27.936	30.746	4257.273	
		+1000 ft	223.113	245.270	259.760	2948.611	3651.439	4368.015	25.315	28.315	31.147	4368.015	
	Airplane Weight	85000.0 (lbs)	208.016	233.593	248.558	2241.053	2903.786	3519.238	20.721	23.721	26.269	3519.238	
		95000.0 (lbs)	219.912	242.079	256.354	2862.196	3555.441	4257.273	24.936	27.936	30.746	4257.273	
		105000.000 (lbs)	231.196	250.604	264.249	3576.278	4299.190	5092.845	29.517	32.517	35.593	5092.845	

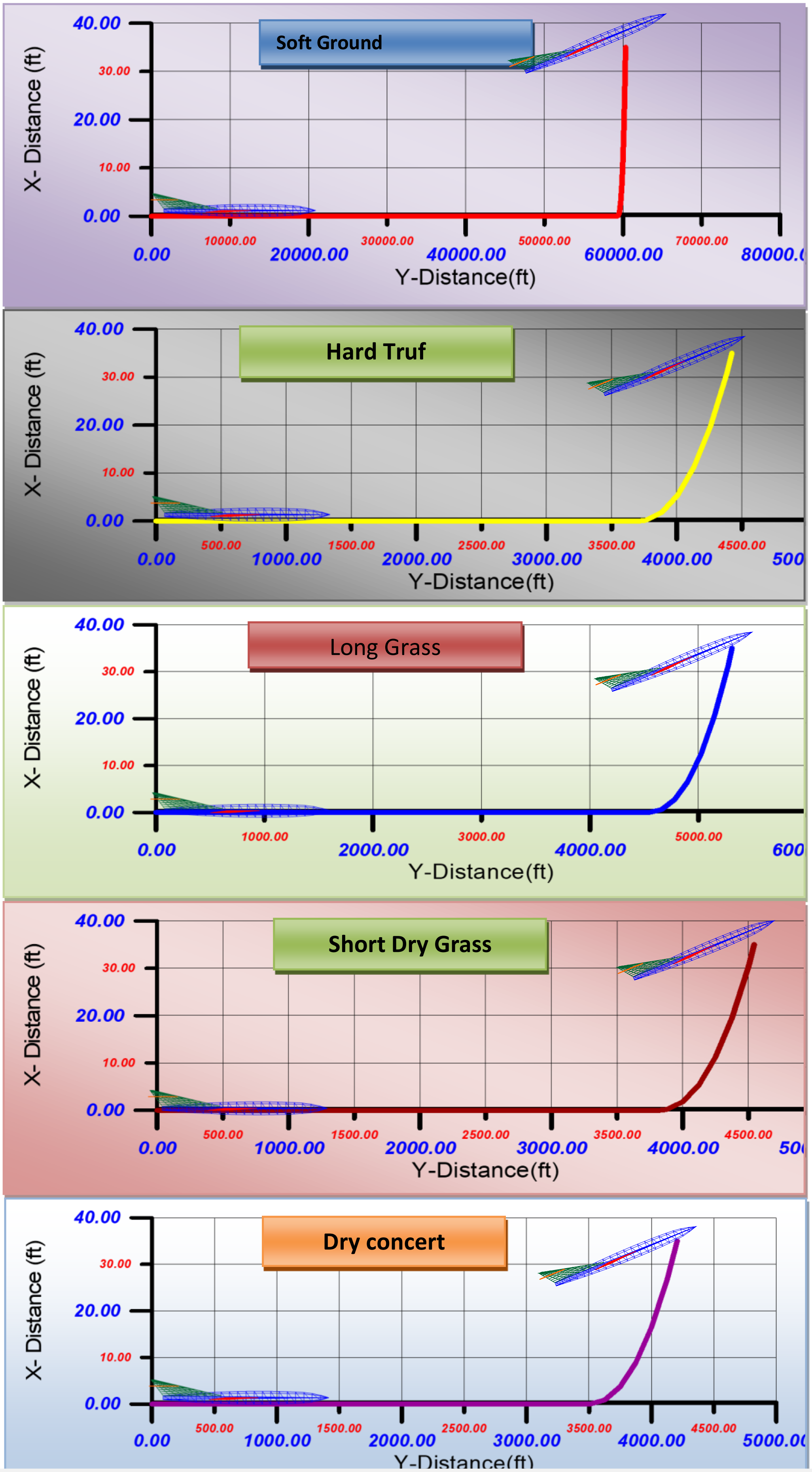

Figure (2) Effect of Runway Construction Material on Lift off distance (Dc-9)

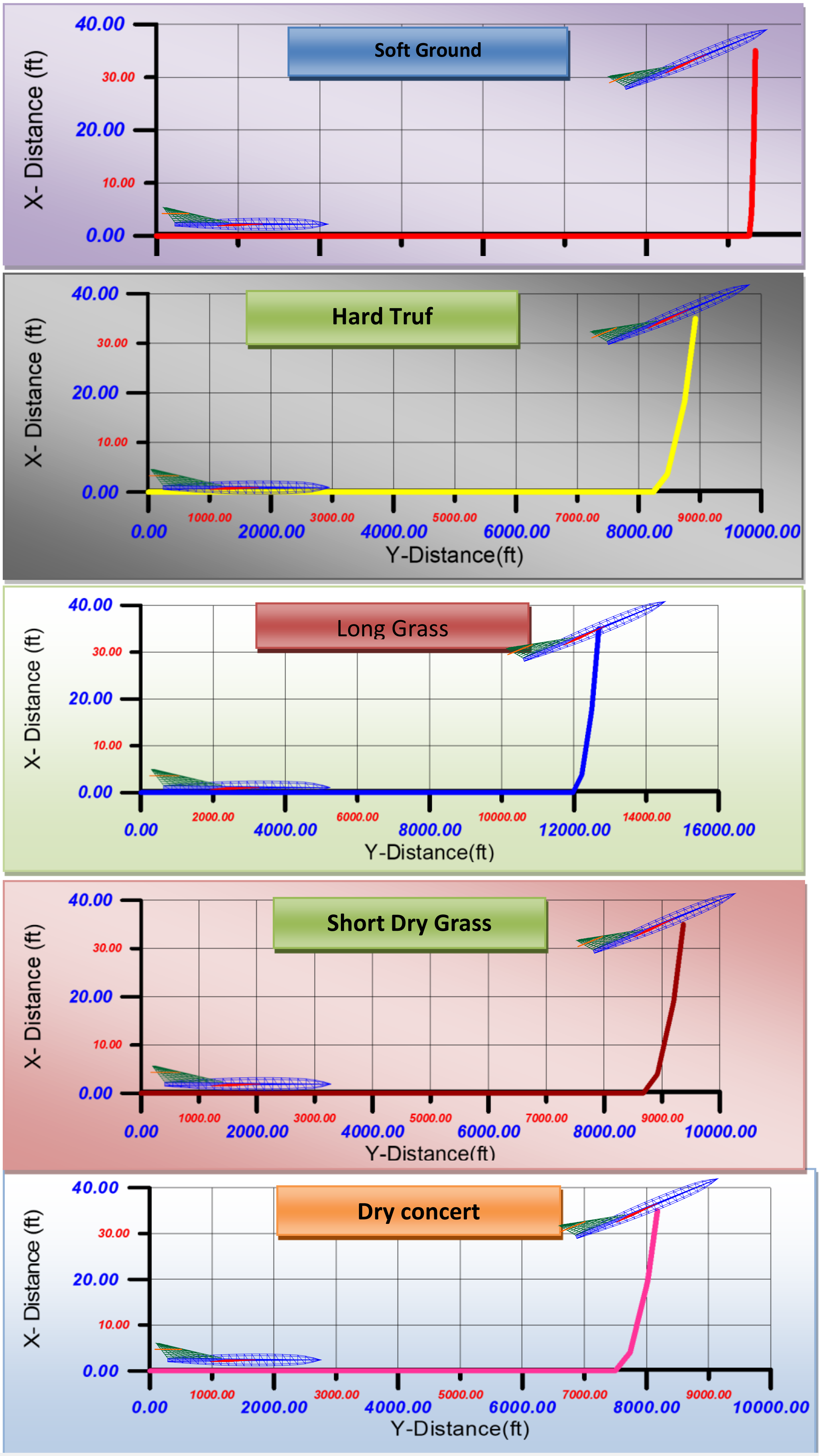

Figure (3) Effect of Runway Construction Material on Lift off distance (747)

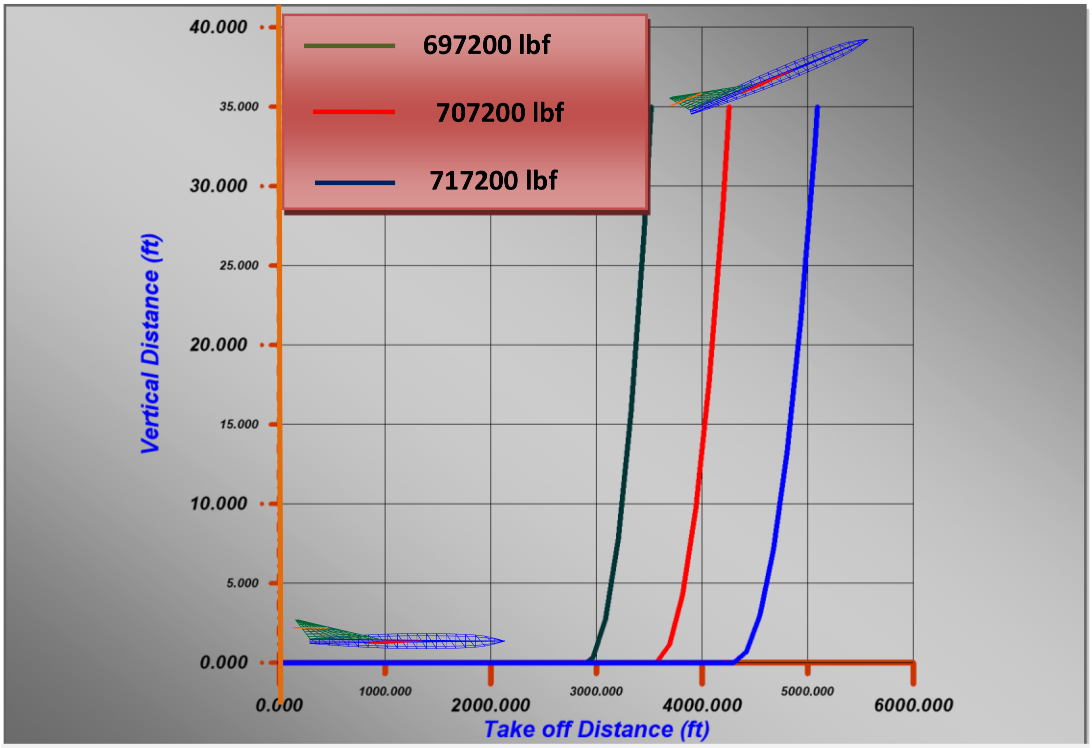

Figure (4) Effect of weight on Lift off Distance (Dc9)

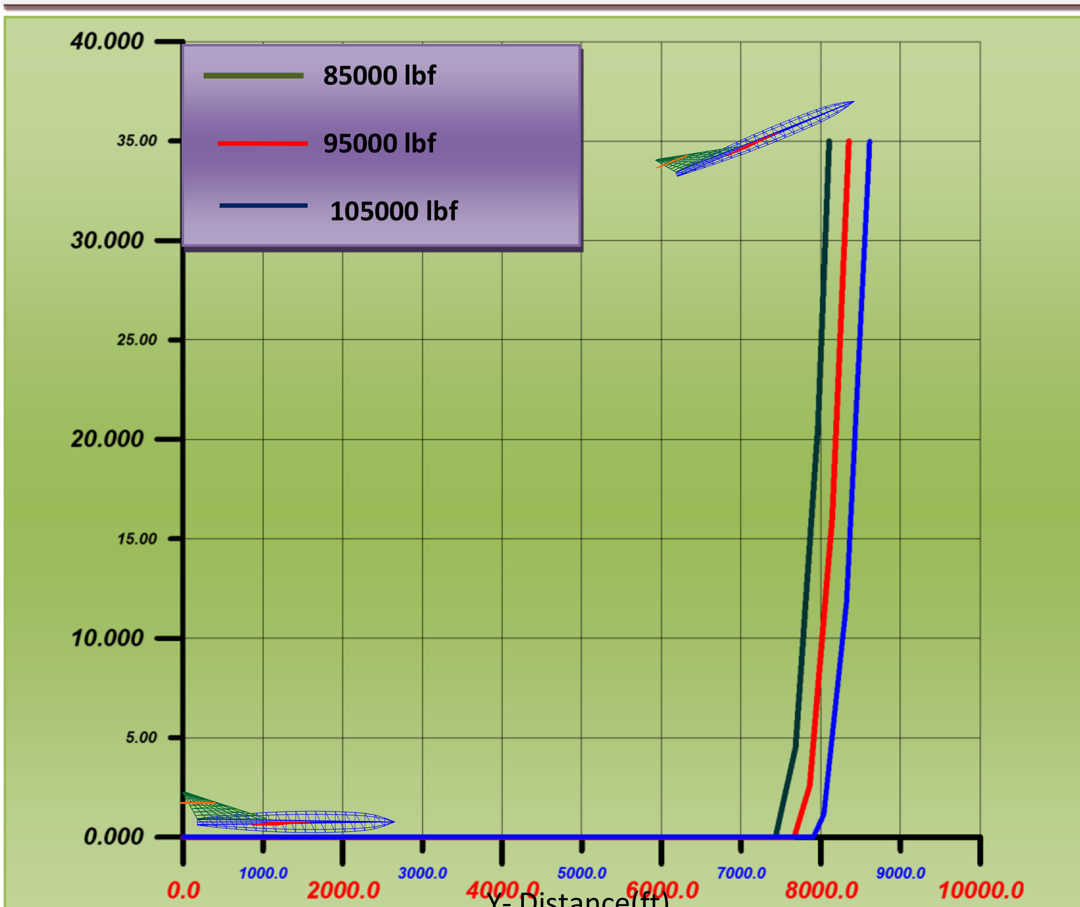

Figure (5) Effect of weight on Lift off Distance (747-400)

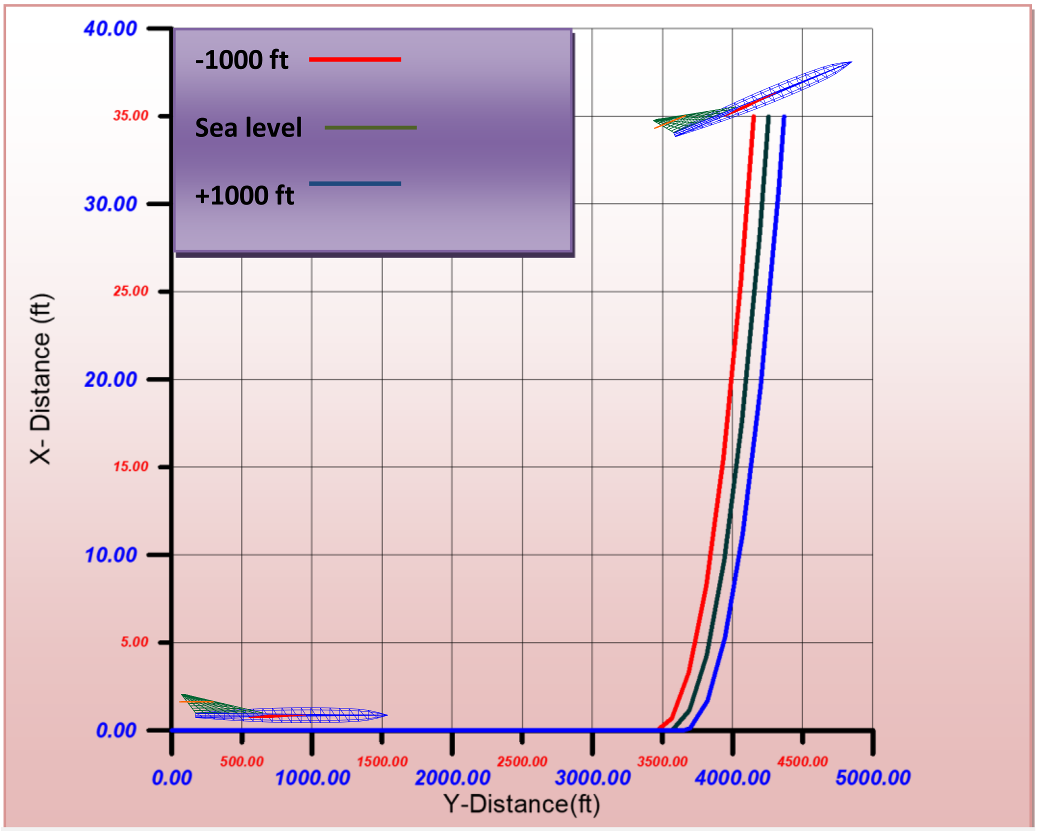

Figure (6) Effect of Runway Height on Lift off Distance (DC9)

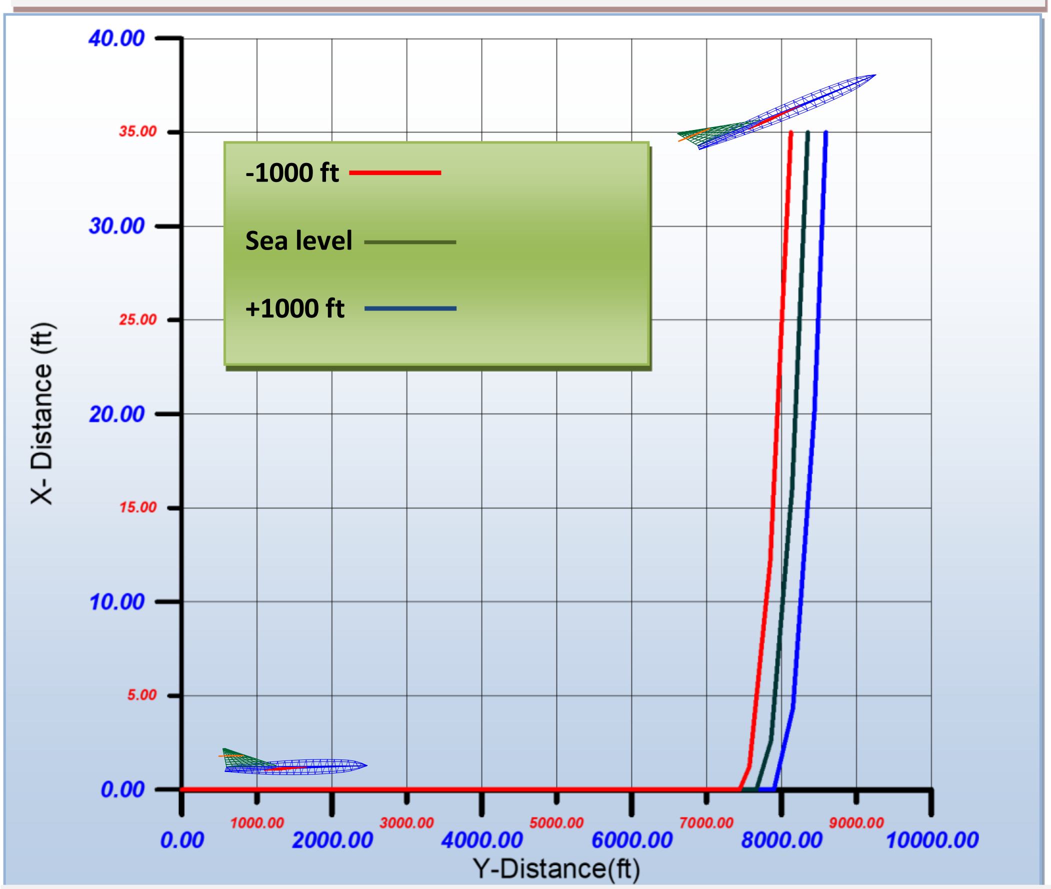

Figure (7) Effect of Runway Height on Lift off Distance (747-400)

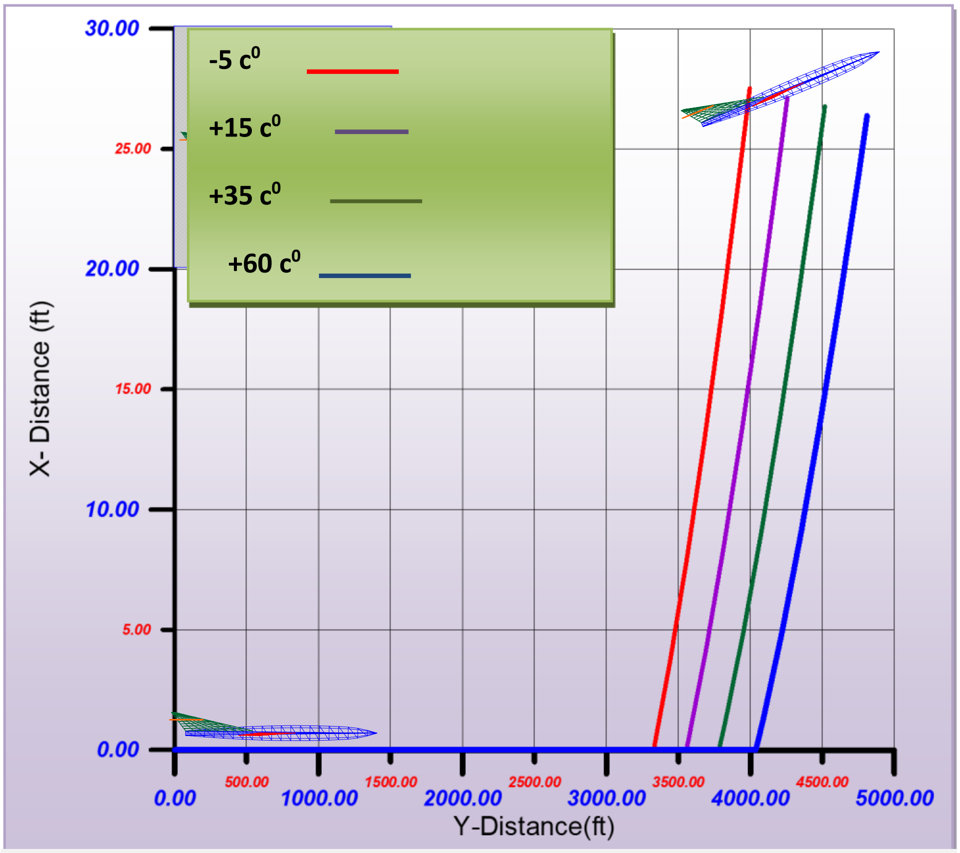

Figure (8) Effect of Weather Temperature on Lift off Distance (747)

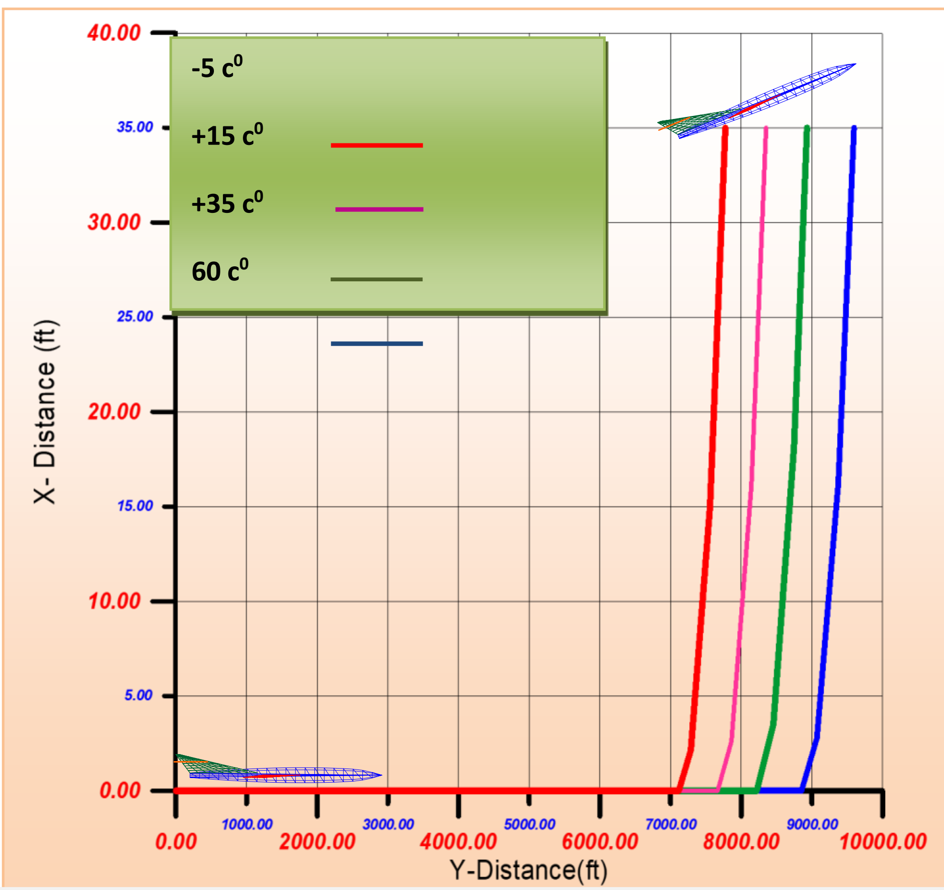

Figure (9) Effect of Weather Temperature on Lift off Distance (747)