Raisbeck Aviation High School Flight Test	
Make	Boeing Commercial Airplanes
Model	Boeing 777-200
EFFECT OF WIND DIRECTION, FLAPS, THRUST, AND WEIGHT ON TAKE-OFF PERFORMANCE	

EFFECT OF WIND DIRECTION, FLAPS, THRUST, AND WEIGHT ON TAKE-OFF PERFORMANCE

FTP: 1.1
VERSION: A
AIRPLANE MAKE AND MODEL: Boeing 777-200

Orig	**/s/**	**Nick** Lead engineer	
App	**/s/**	**Max** Chief pilot	
App	**/s/**	**Larry** Quality control	
App	**/s/**	**Kyle** Test operations	

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Introduction

The test objective is to establish the effect of wind direction, flaps, thrust and weight on take-off performance, specifically takeoff distance.

Given the time and expense of flying actual aircraft, we used X-Plane 9 to obtain our data. X-Plane is an engineering-grade simulator that uses computational fluid dynamics to model the interaction between the environment and aircraft 20 times per second.

We conducted three or more minimum unstick velocity tests for each condition.

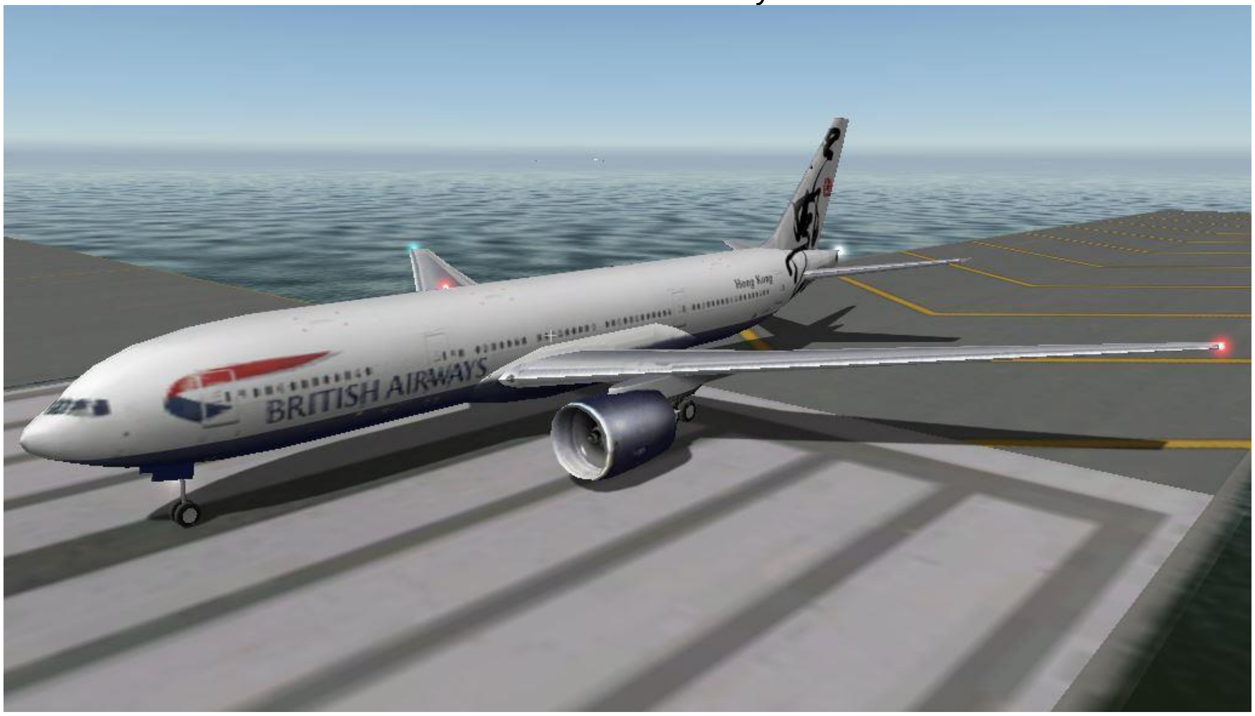

Fig. 1. Boeing 777-200 on runway in simulator

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Success Criteria

Take-off performance testing shall be considered complete when <3 or more> consistent take-offs are performed. In this context, consistent means that take-off distances for a particular condition are within +/- 10% of the mean value.

Test Article Configuration

The test aircraft is the Boeing 777-200 with General Electric GE90-110B1. The airplane shall be in the final flight-ready configuration.

All flights will have the following characteristics in common:
Winds: Calm
Temperature: 60 F
Pressure: 29.92 inHg
Field Elevation: 1,185 ft

Parameter 1: Wind Direction @ 20 kts
Baseline (intermediate value): n/a
Corner condition (low value): 0° off heading
Intermediate low: 45° off heading
Intermediate high: 90° off heading
Corner condition (high value): tailwind (180° off heading)

Parameter 2: Flaps
Baseline (intermediate value): (20)
Corner condition (low value): (5)
Corner condition (medium value): (10)
Corner condition (high value): (15)

Parameter 3: Thrust
Baseline (intermediate value): (80)
Corner condition (low value): N/A
Intermediate low: 70%
Intermediate high: 90%
Corner condition (high value): 70%,90%

Parameter 4: Weight
Corner condition (low value): 308,210 lbs
Intermediate: 500,237 lbs
Corner condition (high value): 632,499 lbs

DATA REQUIRED

Item	**Description**
Data	ON and RECORDING prior to start of test Times (2) Speed (3) Atmosphere (5) Flaps (13) Latitude, Longitude, Altitude (20) Engine power (34) Landing gear vertical force (66)
Flight deck display	Selected parameters displayed on flight deck Times (2) Speed (3) Lat, lon, altitude (20)

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TEST PREREQUISITES

Parameter	Description	Condition #
Temperature	60ºF	1-14
Thrust	100%	1-8, 12-14
Airport elevation	451’	1-14
Wind speed	n/a	1,6-14
Wind direction	n/a	1,6-14
Weight	455609 (lb)	1-11
Flaps	20°	1-5,9-14
Pilot input	After bringing engine to desired power setting, release brakes. Steer aircraft down centerline with yoke full aft. After take-off, ease up on yoke to avoid stalling the aircraft. Pause simulation a 100 ft in the air.	1-14

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TEST REQUIREMENTS

Requirement	Description	Condition #
Wind Direction @ 20 kts	0° off heading	2
	Tailwind (180° off heading)	3
	45° off heading	4
	90° off heading	5
Flaps	5°	6
	10°	7
	15°	8
Thrust	70% thrust	9
	80% thrust	10
	90% thrust	11
Weight	308,210 lbs	12
	500,237 lbs	13
	632,499 lbs	14

RISK MANAGEMENT

Flying minimum unstick velocity tests presents a handful of risks not associated with traditional flights. To minimize risk to the aircraft, crew, and people and structures near the airport, the flights will occur from airports with long runways in sparsely populated areas (e.g., Grant County International, KMWH)

Additionally, pilots and crew shall train and be prepared for the following:

Situation: Bird strike

Hazard: Condition usually occurring at low altitude, such as takeoff or landing when birds are sucked into the engine, or come in contact with the aircraft.

Effect(s):

- Engine out. Engine cuts out because of bird ingested into the engine. Possible fire.
- Damaged nose cone, wing, or windscreen. Bird impacts aircraft at high speed, causing damage.

Mitigation

- Scarecrow tactic. Airport vehicles drive down runway honking horns to scare the birds away.
- Fake coyotes and wolves placed on airport surfaces to scare birds away from the airport vicinity.
- Blank shotgun shell fires on the hour to scare birds.

Alleviation

- Follow emergency procedures for the type of event that has occurred. (Cactus 1549)

Situation: Engine failure during take-off

Hazard: Engine is starved of fuel, damaged fan blade(s), hydraulic pressure loss.

Effect(s):
- Loss of the engine
- Single engine climbout

Mitigation
- Routine inspections of aircraft’s engine(s)

Alleviation
- If issue occurs before V1 speed, RTO procedures. If after V1 speed, shut down the problem engine and assert counter rudder dominance.

Situation: Stalled aircraft
Hazard: Aircraft’s wing stops generating lift because of significant angle of attack.

Effect(s):
- At low altitude, stall may not be recoverable, sending the aircraft into the ground.
- Stalls at high altitude will still cause the aircraft’s nose to drop, but more room will be available to establish a safe operating speed before hitting the ground.

Mitigation
- Keeping airspeed above stall speed by monitoring thrust and climb pitch (angle of attack)

Alleviation
- Push the nose of the aircraft down to regain speed and lift from the wings.

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Test Conditions

Standard Procedure

Provide a numbered list of steps the test pilots should follow.

1. Grant County International (KMWH)
   a. Runway 14L
   b. Field Elevation 1,185 ft
2. Winds calm, 60 deg F, pressure 29.92 inHg
3. 455, 609 lbs
4. 20° flaps
5. TOGA power full thrust
6. Start time: beginning of takeoff roll
7. Stop time: 50 feet above ground

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Condition Specific Notes

Each Condition repeated 3 times

Condition.Trial	Wind Direction In (°) @ 20kts	Thrust	Flaps (°)	Weight (lb)
1.1-12	n/a	100%	20°	455609
2.1-3	155°	100%	20°	455609
3.1-3	355°	100%	20°	455609
4.1-3	200°	100%	20°	455609
5.1-3	245°	100%	20°	455609
6.1-3	n/a	70%	20°	455609
7.1-3	n/a	80%	20°	455609
8.1-3	n/a	90%	20°	455609
9.1-3	n/a	100%	5°	455609
10.1-3	n/a	100%	10°	455609
11.1-3	n/a	100%	15°	455609
12.1-3	n/a	100%	20°	308210

13.1-3	n/a	100%	20°	500237
14.1-3	n/a	100%	20°	632499

DATA

Wind Direction

To test the effect of a wind direction on take-off distance, we configured the plane as follows: 20 kts winds, KMWH (Moses Lake Runway), Boeing 777-200, 60°F, 455609 (lb), and 29.92 inHg.

During the testing we acquired the following data:

- At 155° from magnetic north or 0° off runway heading, the average take-off distance was 3,338 feet.
- At 335° from magnetic north or 180° off runway heading, the average take-off distance was 5,034 feet.

From these data, it appears that for every 10° increase in wind direction, take-off distance increases by 98 ft. From 50°- 180°, takeoff distance increases by ~98 ft per 10°. The graph does not follow a linear trend but we know that after 180° it will curve down to 360° with the same results at 0° and so on. The full table of data can be found on page 21.

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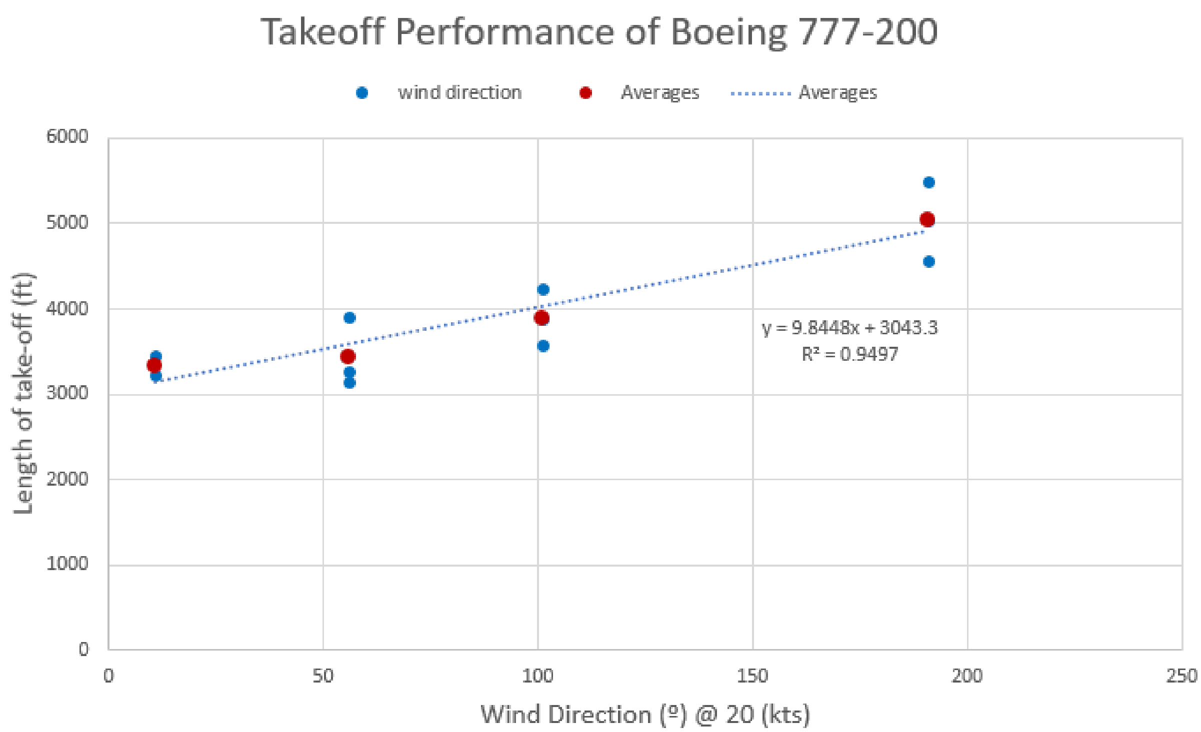

Fig. 2. Length of take-off roll vs. Wind Direction @ 20 kts

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Degree of Flaps

To test the effect of flaps on take-off distance, we configured the plane as follows:
Weight: 455609 (lb)
Temperature: 60° F
Field Elevation: 1185 ft
Runways: 14L

During the testing we acquired the following data:

At 5 degrees, the average take-off distance was 5955.46 feet.
At 15 degrees, the average take-off distance was 4753.42 feet.

From these data, it appears that for every 1 degree increase on flaps, takeoff distance would decrease by 120.5 feet. The full table of data can be found on page 22

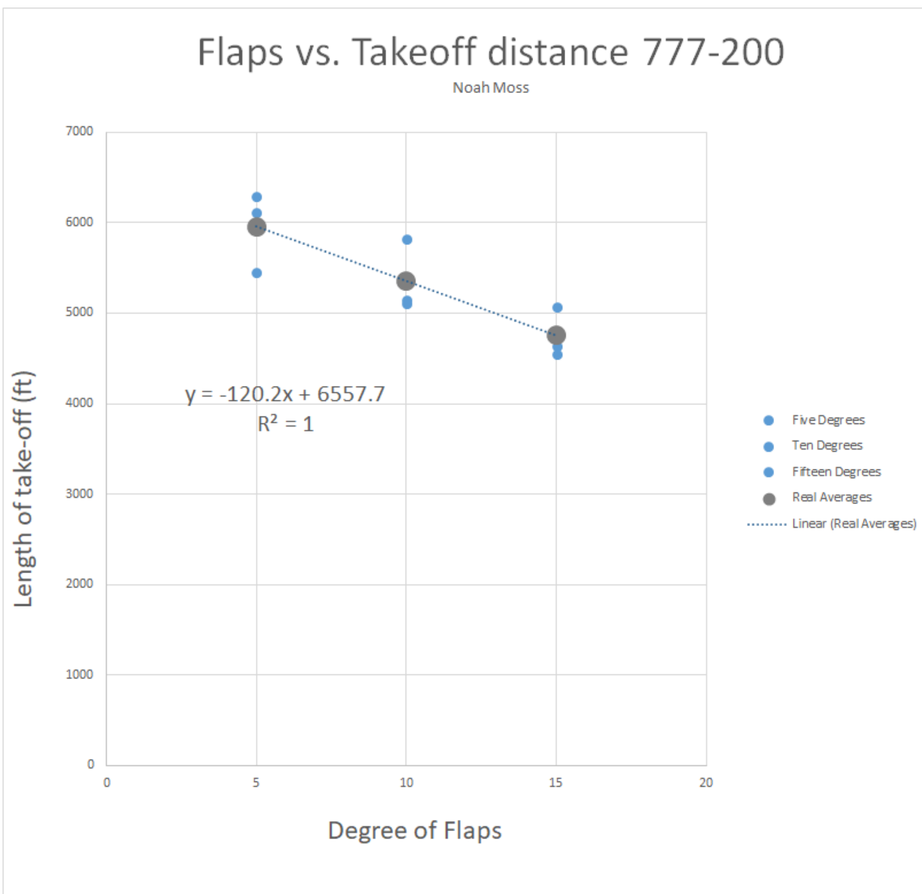


Fig. 3. Length of take-off roll vs. Flaps

Parameter 3

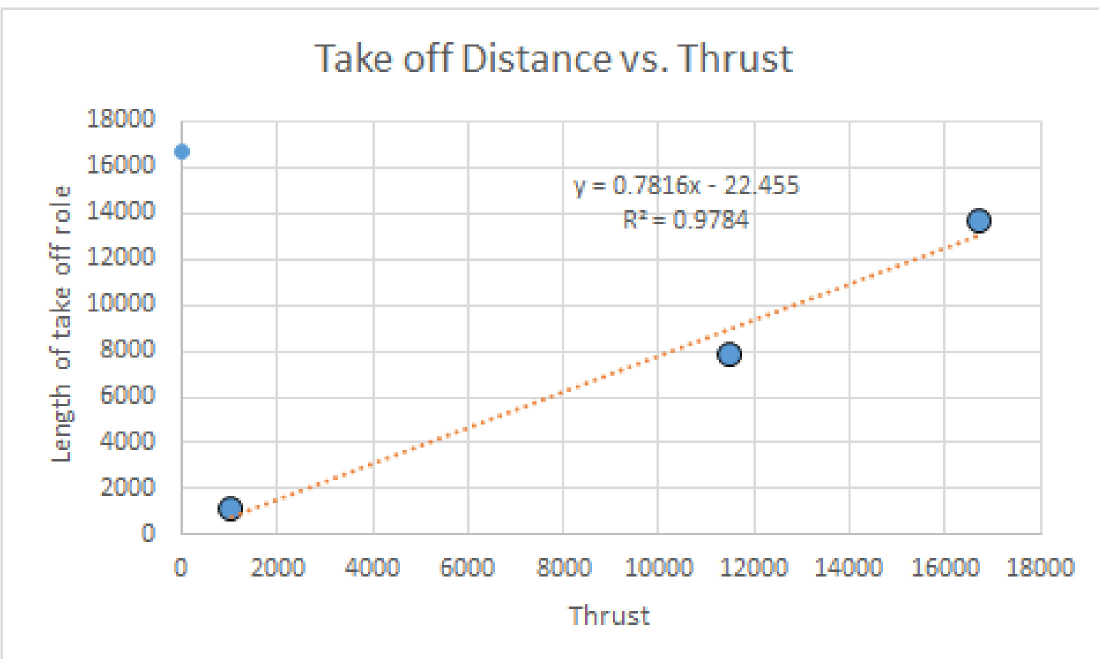
To test the effect of thrust to take-off distance, we configured the plane as follows: We tested engine powers of 70%,80%,and 90%.

During the testing we acquired the following data:

At At 70% power in the engine, the average take-off distance was 1600 feet.
At At 90% power in the engine, the average take-off distance was 1150 feet.

From this data, it appears that for every 10% increase in engine power, the take-off distance decrease while the direction of the plane goes up. The full table of data can be found on page 23.

Fig. 4. Length of take-off roll vs. Thrust



Weight

To test the effect of a weight on take-off distance, we configured the plane as follows:
Flaps: 20
Temperature: 60° F
Field Elevation: 1185 ft
Runways: 14L

During the testing we acquired the following data:

- At the lowest weight tested, 308,210 lbs, the average take-off distance was 1,260 feet.
- At the highest weight tested, 632,499 lbs, the average take-off distance was 5,210 feet.

From these data, it appears that for every 10,000 lb increase in weight, take-off distance increases 120 ft. The full table of data can be found on page 26.

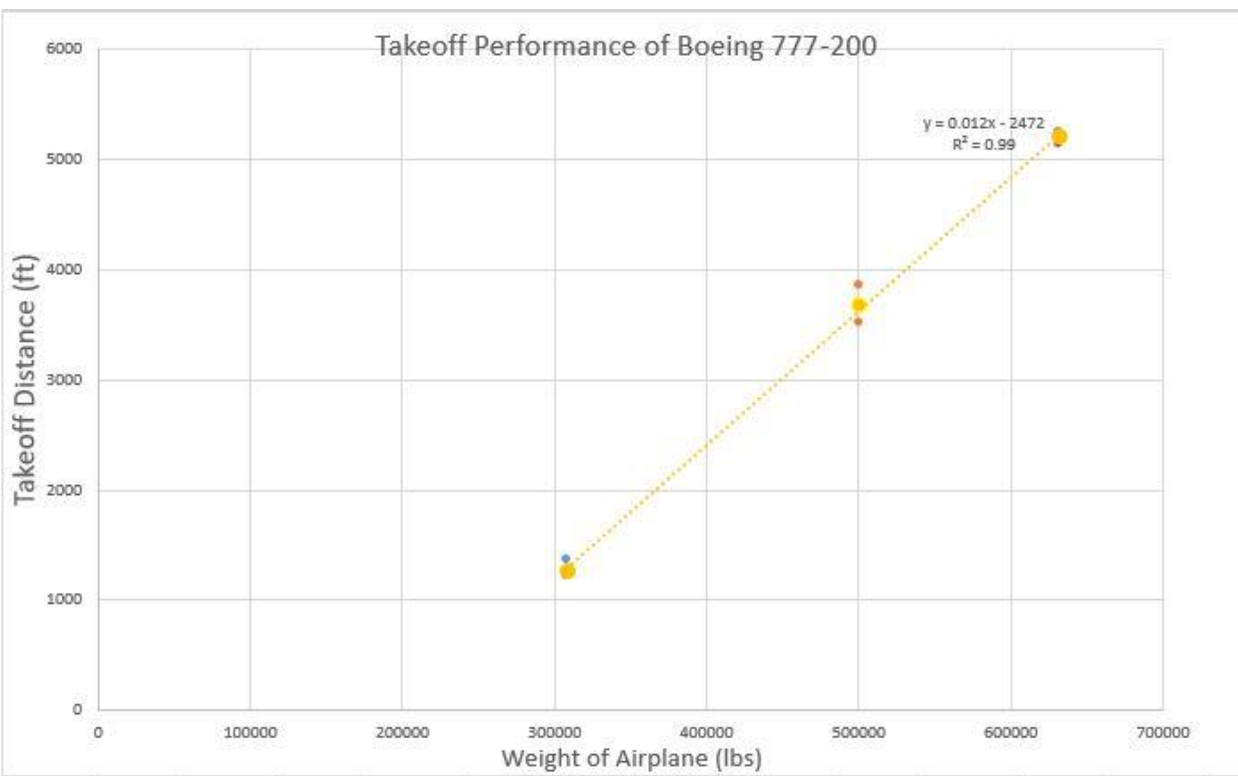


Fig. 5. Length of take-off roll vs. weight

ANALYSIS

Wind Direction

When the parameter wind direction was changed it, affected the takeoff distance. When the wind direction changes from headwind to tailwind the takeoff distance increased. This matches our expectations because when wind is coming directly at the wings at 20 kts, it increases the lift and when a tailwind of 20 kts, it slows the planes takeoff time because it has to build up airspeed to 20 kts to takeoff. We expect takeoff distance to decrease again when wind direction changes from 180°- 360°. When at a cross wind or 90° off heading, we expect that the wind speed will not affect the take-off distance because the net force of a cross wind in a linear path is equal to the net force of a take-off with no wind. We can calculate the headwind force with, $(cos(\theta) = Headwind/Overallwind$this will show us the amount of force that affects the takeoff distance.

Next steps would include more manipulated variables to better show the trend of wind direction and testing additional aircraft to see how their takeoff distance changes in length of runway vs. wind direction.

Flaps

When the flaps increased, runway takeoff distance decreased.This matches our expectations because when the flaps increases, the amount of air getting deflected under the wing increased, thus increasing lift. The area of the wing and the coefficient of lift increases when the degrees of flaps increase. The lift equation ($L = \frac{1}{2}pv^2AC_L$) shows that when the area increase, lift increases. From the data, it shows that for every 1 degree the flaps increase, takeoff distance decreased by 120.5 feet.

Next steps would include changes in mass, so these test can be better applied to real world situations.

Thrust

When thrust is decreased the take off distance increases. When thrust is increased the take off distance decreases. This matches our expectations, because when the plane travels at a higher speed the air pressures around the wing increase. When the plane isn’t at full thrust it takes a longer time for the aircraft to reach the speed necessary to generate lift. (Weight to thrust ratio). We expected the take off distance to be increase if there was a decreases in thrust.

Weight

When weight is increased, runway takeoff distance increases. When weight is decreased, runway takeoff distance decreases. This is due to Newton's Second Law and F=MA. These results match our expectations because when weight increases, the acceleration of the aircraft will decrease, thus, taking longer for the correct amount of air to flow around the wings to create the lift required for takeoff. Additionally, when mass increases, more lift is required to get the airplane into the sky. In the equation $L = C_L \frac{1}{2} \rho v^2 A$, we know that L, lift, has to be greater in heavier airplanes to counter the weight increase. With a lighter airplane, the acceleration increases, so the time it takes to get to V_r speed decreases.

Next steps could include performing more tests to continue the trend and test the mathematical model, or even testing in an additional aircraft to see if the change in weight vs. runway length is consistent.

VALIDATION OF SIMULATOR

http://www.boeing.com/assets/pdf/commercial/airports/acaps/777_2lr3er.pdf

Wind Direction data were not readily available.

As we compared the Boeing Commercial Aircraft (BCA) data to our own, they both shared the trend, that when one increases the flaps the takeoff distance decreases. One example from the BCA, shows when the flaps were at 5 with a weight of 455,609 lbs the takeoff distance was around 9,000 ft, verses when the flaps were at 20 the takeoff distance was around 7,500 ft. The simulator shows that when a 777-200 with the weight of 455,609 lbs with the flaps at 5 the average takeoff distance was 5,955 ft. The possible reason why the data from the simulator is different the BCA is that the conditions for the BCA might have been unexpectedly changed by the weather.

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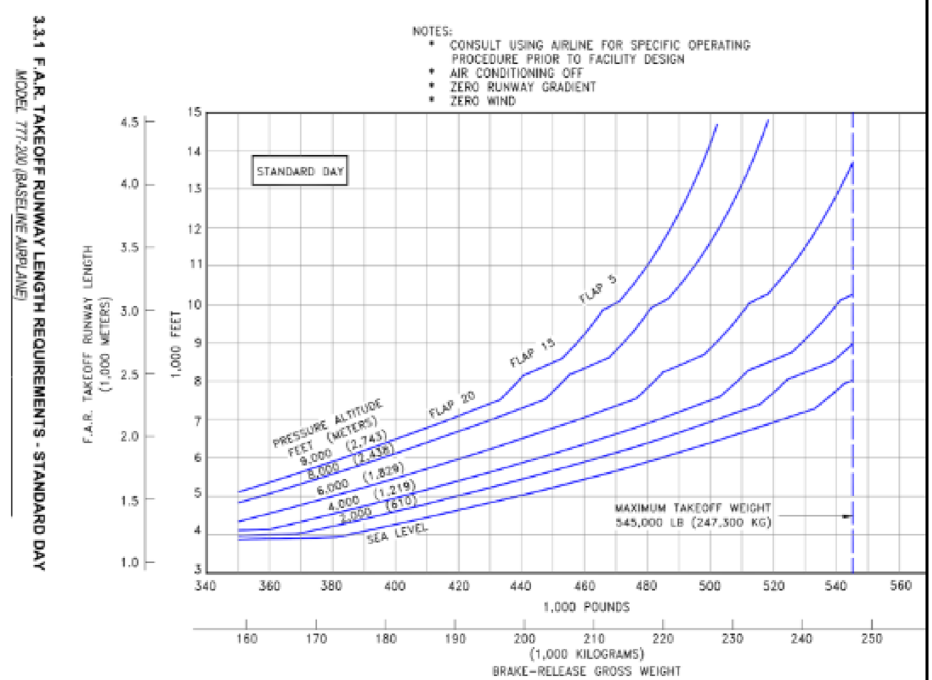

Fig. 6. BCA flaps graph

When studying the graph put forth by BCA, it shows that when weight is increased, takeoff distance is increased. When we performed our tests, this was true. For example when we test with a weight of 632,499 lbs, takeoff distance was 5,237 ft. In the graph from Boeing, with a weight of 630,000 lbs, the takeoff distance is ~7,000 ft. Furthermore, at 308,000 lbs in the simulator, takeoff distance was marked at 2,496.57 ft. From Boeing's graph, 300,000 lbs calculates to a 4,500 ft takeoff distance. We can tell from these results, that the actual takeoff distance is longer than that of the simulator used.

These differences could be due to a contrasting power plant type, differences in test environment, and or the consistency of the tests.

APPENDIX

Technical specifications of Boeing 777-200

- 2,200 gallons of fuel per hour
- 297,300 lbs empty
- 5,240 nm range
- 43,100 ft service ceiling

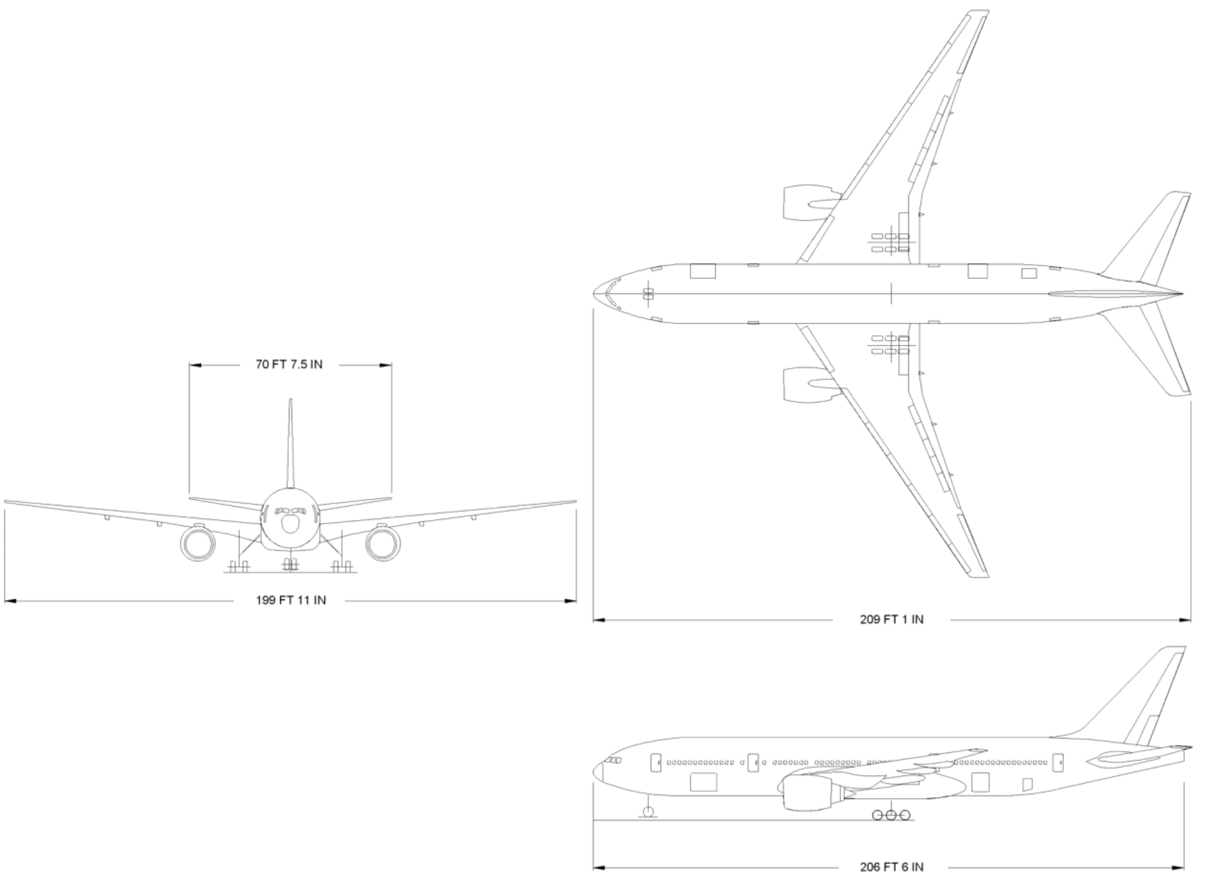

Fig 7. Diagram of Boeing 777-200

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Data for length of take-off rolls are found on the following pages.
31c: Flight Test Data Log 2018 - Analysis Sheet

The length of take-off rolls was calculated in the following way:

1. Accurately and clear describe how take-off roll was calculated.
    a. How did we determine acceleration? Include steps for converting from mph to ft/s.
        i. $a = \frac{vf - vi}{t}$ 1 mph = 5,280 feet
    b. How did we determine distance?
        i. $d = \frac{1}{2}at^2 \quad + Vi \times t$ or $d = \ V\ ave \times t$
    a. How did we determine final velocity?
        i. $Vf = a \times t + Vi$
    b. How did we determine average velocity?
        i. $Vave = \frac{Vf + Vi}{2}$
2. Provide an example with some of your data.

$$a = 14.3 = \frac{73.33}{5.1}$$
$$d = \frac{1}{2} 14.3 \times 5.1^2$$
$$d = 3937.4\ ft$$

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Baseline Data

Each pilot flew the same condition to ensure that pilots were flying consistently. The mean take-off distance was 3,555 feet. The difference between the shortest take-off distance (condition 1.12) and the longest take-off distance (condition 1.2) was 1753.7 feet, 49.3% of mean take-off distance.

Cond	Wind Direction	Flaps	Thrust	Weight	$t_{\text{to reach 50 mph}}$ (s)	$t_{\text{take off}}$ (s)	Acc (ft/s per s)	Take-off distance (ft)	pilot	Verified by
1.1	n/a	20°	Max	455609 (lb)	5.1	23.5	14.3	3937.4	LB	KT
1.2					5.0	25.0	14.7	4590.2	LB	KT
1.3					5.0	21.9	14.7	3534.7	LB	KT
1.4					3.5	15.4	20.9	2486.2	NM	MW
1.5					3.6	16.5	20.2	2746.4	NM	MW
1.6					3.5	16.4	21.	2815.4	NM	MW
1.7					12.2	21.0	5.5	13727	KT	LB
1.8					10.4	13.8	5.5	11823	KT	LB
1.9					4.7	12.4	16.9	1135	KT	LB
1.10					4.9	15.7	15	2950.9	MW	NM
1.11					3.6	12.1	20.3	2496.6	MW	NM
1.12					3.5	15.2	20.8	2386.5	MW	NM

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Parameter 1: Wind Direction

With flaps set to 20°, trust set to max, and weight set to 455,609 lb, the table below shows results of take-off performance when we modified wind direction at 20 kts.

Cond	Wind Direction	t to reach 50 mph (s)	t take off (s)	Acc (ft/s per s)	Take-off distance (ft)	pilot	Verified by
2.1	0° off heading	5.0	21.4	14.6	3340	Bullock	Welliver
2.2		5.0	21.0	14.7	3220	Bullock	Welliver
2.3		4.9	21.4	15.0	3450	Bullock	Welliver
3.1	Tailwind (180° off heading)	4.8	26.8	15.3	5490	Bullock	Welliver
3.2		4.9	25.9	15.0	5040	Bullock	Welliver
3.3		4.8	24.4	15.4	4570	Bullock	Welliver
4.1	45° off heading	5.0	23.0	14.7	3910	Bullock	Welliver
4.2		4.9	20.5	14.9	3140	Bullock	Welliver
4.3		4.9	21.0	14.8	3280	Bullock	Welliver
5.1	90° off heading	4.9	21.9	14.9	3580	Bullock	Welliver
5.2		5.0	22.9	14.8	3880	Bullock	Welliver
5.3		4.8	23.5	15.3	4230	Bullock	Welliver

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Parameter 2: Flaps
With wind direction set to n/a (0 kts), thrust set to max, and the weight was set to 455,609 lbs, the table below shows results of take-off performance when we modified the flaps.

Cond	Degree of Flaps	$t_{\text{to reach 50 mph}}$ (s)	$t_{\text{take off}}$ (s)	Acc (ft/s per s)	Take-off distance (ft)	pilot	Verified by
6.1	5°	5.2	27.7	14.19	5456.9	Moss	Bullock
6.2		5.2	29.8	14.17	6294.4	Moss	Bullock
6.3		5.2	29.4	14.16	6115.1	Moss	Bullock
7.1	10°	5.1	26.6	14.51	5150.	Moss	Bullock
7.2		5.1	28.5	14.28	5817.9	Moss	Bullock
7.3		5.1	26.6	14.40	5106.3	Moss	Bullock
8.1	15°	5.0	24.9	14.61	4546.8	Moss	Bullock
8.2		5.0	25.2	14.57	4639.9	Moss	Bullock
8.3		5.1	26.5	14.43	5073.5	Moss	Bullock

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Parameter 3: With wind direction set to n/a (0 kts), flaps set to 20 degrees, and Weight set to 455609, the table below shows results of take-off performance when we modified Thrust.

Cond	Thrust	$t_{\text{to reach 50 mph}}$ (s)	$t_{\text{take off}}$ (s)	Acc (ft/s per s)	Take-off distance (ft)	pilot	Verified by
9.1	70% thrust	20	21.0	3.7	16696.25	Kael	Max
9.2		21	20.4	3.4	10647	Kael	Max
9.3		23	21.7	3.1	13838.4	Kael	Max
10.1	80% Thrust	14	13.8	5.5	11459	Kael	Max
10.2		20	14.0	3.7	5240	Kael	Max
10.3		14.	14.4	5.5	6948	Kael	Max
11.1	90% Thrust	6	13.3	15.1	1208.6	Kael	Max
11.2		5	12.4	15.7	1209.9	Kael	Max
11.3		4	12.0	16.9	1218.4	Kael	Max

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Parameter 4: Weight
With wind direction set to n/a (0 kts), flaps set to 20, and thrust set to maximum, the table below shows results of take-off performance when we modified weight.

Cond	Weight (lbs)	$t_{\text{to reach 50 mph}}$ (s)	$t_{\text{take off}}$ (s)	Acc (ft/s per s)	Take-off distance (ft)	pilot	Verified by
12.1	308,210	4.7	13.3	15.45	2950.93	Welliver	Bullock
12.2		4.7	12.4	15.72	2496.57	Welliver	Bullock
12.3		4.3	12.0	16.92	2386.51	Welliver	Bullock
13.1	500,237	5.4	23.2	13.61	3655.63	Welliver	Bullock
13.2		5.4	22.7	13.63	3514.86	Welliver	Bullock
13.3		5.4	23.9	13.49	3858.60	Welliver	Bullock
14.1	632,499	7.0	31.6	10.50	5248.20	Welliver	Bullock
14.2		7.0	31.6	10.52	5237.83	Welliver	Bullock
14.3		6.9	31.1	10.64	5130.11	Welliver	Bullock