Assignment 3: Aircraft Performance Calculations

Solution Instructor: Trani

Problem 1

Using the fundamental equation of motion explained in class and the fundamental lift equation (see equations below) explain in three sentences, the following questions:

$\frac{dV}{dt} = \left(\frac{1}{m}\right)(T - D - F_f - (mg\sin\phi))$ $L = \frac{1}{2}\rho V^2 S C_l$ $D = \frac{1}{2}\rho V^2 S C_D$ $F_f = (mg\cos\phi - L) f_{roll}$ $T = f(V, \rho)$	$V_{stall} = \sqrt{\frac{2mg}{\rho S C_{l\max}}}$

a) The effect of airport elevation in takeoff speed.

Airport elevation lowers air density. Using the fundamental lift equation, stall and takeoff speeds increase for the same aircraft mass. Lower density reduces mass flow rate (the amount of air entering the turbofan engine) and hence reduces thrust. Lower thrust produces lower acceleration and hence increases the time to reach takeoff speed. The result is an increase in runway length. The causal effects are non-linear.

b) The effect of airport elevation in aircraft acceleration during takeoff.

Airport elevation lowers air density. Lower density reduces mass flow rate (the amount of air entering the turbofan engine) and hence reduces thrust. Lower thrust produces lower acceleration and hence increases runway length. The causal effects are non-linear.

c) The effect of airport elevation on engine thrust.

Airport elevation lowers air density. Lower density reduces mass flow rate (the amount of air entering the turbofan engine) and hence reduces thrust. The effect is nonlinear because density changes nonlinearly with airport elevation.

d) The effect of runway gradient on aircraft acceleration.

Uphill gradient increases the retarding force to accelerate and aircraft to a takeoff speed.Uphill gradient increases runway length.

e) The effect of aircraft mass in the acceleration during takeoff.

Aircraft mass reduces acceleration on the runway (Newton's second law of motion).

f) The effect of mass and airport elevation on takeoff distance.

Aircraft mass reduces acceleration on the runway and increases the takeoff distance.

Problem 2

A new airline is evaluating two aircraft to operate flights from Washington, Reagan Airport (DCA) to two important southern destinations. The following table shows the aircraft proposed by airline executives to operate from DCA. The critical stage lengths the airline would like to fly with the selected aircraft are: a) DCA-DFW (1,100 nm with detour factor) and b) DCA-MIA (850 nm with detour factor). The critical route is DCA-DFW.

Table 1. Aircraft Considered in the Airline Evaluation.

Aircraft Considered
Boeing 737-8 Max with CFM LEAP-1B28 engines. Aircraft maximum design takeoff weight is 181,000 lb. 162 seats in a two-class layout.
Boeing 737-800 (with winglets) powered by two *CFM56-7B24/-7B26/-7B27 engines at 26,000 LB SLST)*). Aircraft maximum design takeofff weight is 174,200 lb. The aircraft has 160 seats in a two-class layout.

The design airport temperature used should be the average of the daily high temperatures of the hottest month of the year. More detailed information about the airport can be found at the AIRNAV database available on the web at: http://www.airnav.com/airports/ or visit the airport site.

In your analysis use the latest version of the Boeing documents for airport design (http://128.173.204.63/courses/cee5614/sites_ce_5614.html#Aircraft_Data).

a) Find the average stage length to be flown between each one of the critical OD airport pairs.

The critical stage lengths the airline would like to fly with the selected aircraft are: a) DCA-DFW (**1,100 nm** with detour factor) and b) DCA-MIA (850 nm with detour factor). The critical route is DCA-DFW.

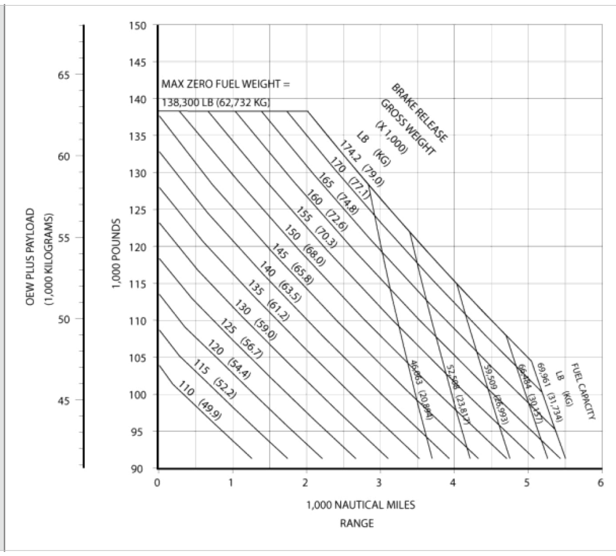
b) Find the runway length needed for each one of the aircraft operating the critical route. Determine if DCA has enough runway length to support these flights.

DCA design temperature is 88.3 degrees (31.3 deg. C.). DCA field elevation is 14 feet. ISA temperature is 58.95 deg. F. (14.97 deg. C.). Temperature offset is 29.35 deg. F. (16.3 deg. C.). **Use the ISA + 15 deg. C. (ISA + 27 deg. F.) runway design charts.**

Table 2. Analysis of Boeing 737-8 Max and Boeing 737-800 with Full Passenger Load.

Parameter	Boeing 737-8 Max	Boeing 737-800
OEW (lbs)	99,000	91,300
MTOGW (lbs)	181,000	174,200
Passenger Seats	162	160
Passenger Load (lbs)	35,640	35,200
OEW + Payload (lbs)	134,640	126,500
Fuel (lbs)	19,360	31,500
DTW (lbs)	**154,000**	**158,000**
Stage length (nm)	1,100	1,100
Fuel per passenger (lbs)	120	197
Runway Length needed (feet)	**5,200**	**6,200**
Runway length Available	7,169	7,169
SAR (nm/lb)	0.057	0.035

CHARACTERISTICS	UNITS	737-800, -800W			737-800BCF
MAX DESIGN	POUNDS	156,000	173,000	174,700	174,700
- TAXI WEIGHT	KILOGRAMS	70,760	78,471	79,242	79,242
MAX DESIGN	POUNDS	155,500	172,500	174,200	174,200
- TAKEOFF WEIGHT	KILOGRAMS	70,534	78,245	79,016	79,015
MAX DESIGN	POUNDS	144,000	144,000	146,300	146,300
- LANDING WEIGHT	KILOGRAMS	65,317	65,317	66,361	66,360
MAX DESIGN	POUNDS	136,000	136,000	138,300	138,300
- ZERO FUEL WEIGHT	KILOGRAMS	61,689	61,689	62,732	62,731
OPERATING	POUNDS	91,300	91,300	91,300	80,800
- EMPTY WEIGHT (1)	KILOGRAMS	41,413	41,413	41,413	36,651
MAX STRUCTURAL	POUNDS	44,700	44,700	47,000	47,000
- PAYLOAD	KILOGRAMS	20,276	20,276	21,319	21,319
SEATING CAPACITY (1)	TWO-CLASS	160	160	160	N/A
	ALL-ECONOMY	184	184	184	N/A
MAX CARGO VOLUME	CUBIC FEET	1,591	1,591	1,591	6,581
- LOWER DECK (2)	CUBIC METERS	45.1	45.1	45.1	186.4
USABLE FUEL	US GALLONS	6875	6875	6875	6875
	LITERS	26,022	26,022	26,022	26,022
	POUNDS	46,063	46,063	46,063	46,063
	KILOGRAMS	20,894	20,894	20,894	20,894



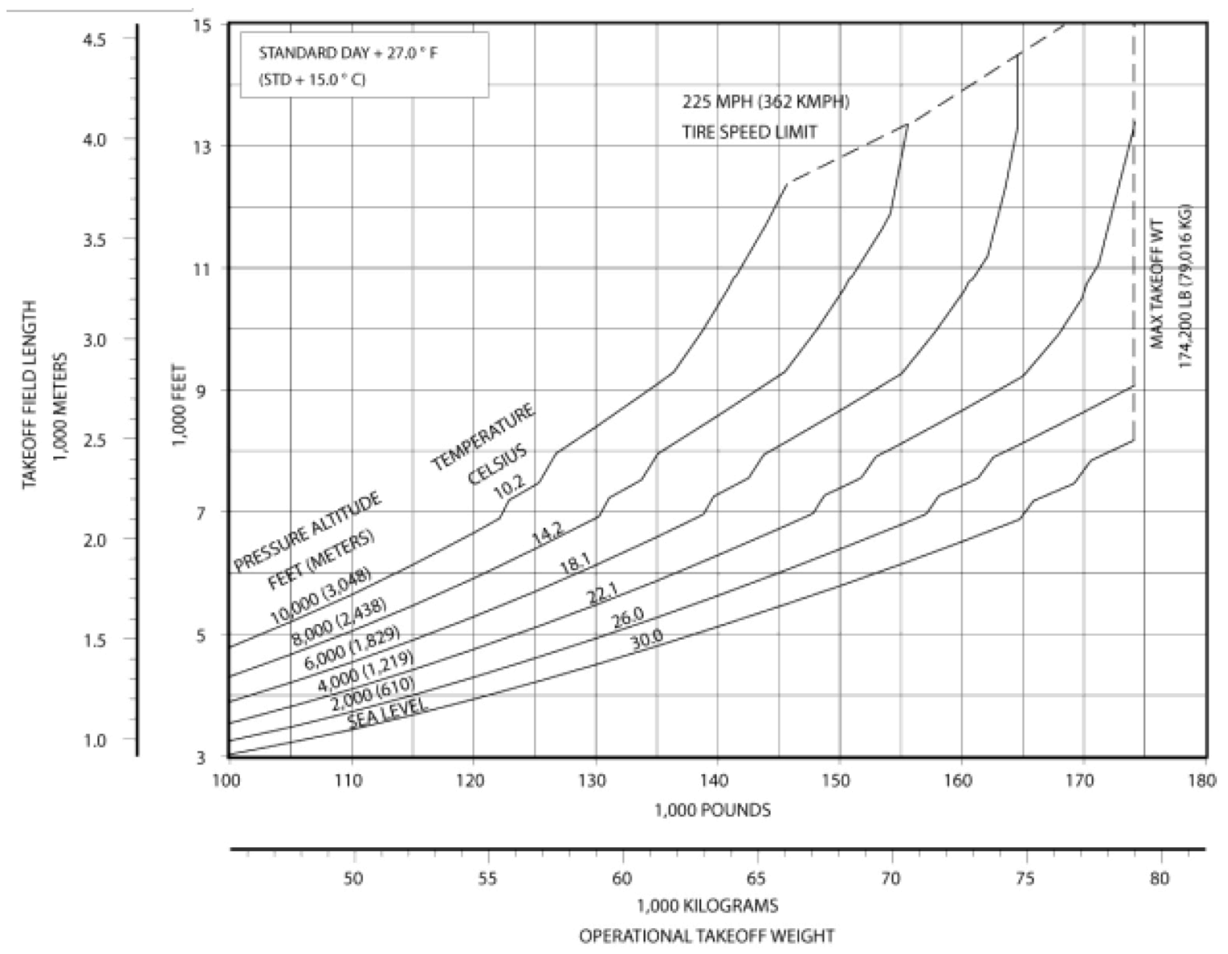
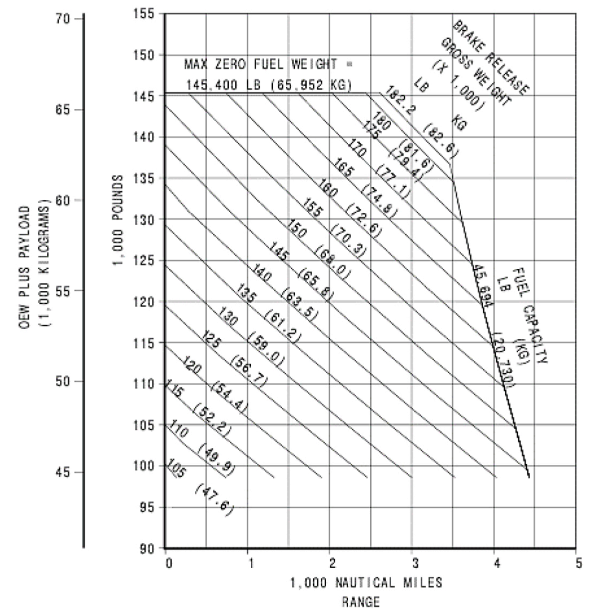


Figure 1. Boeing 737-800 Information

CHARACTERISTICS	UNITS	MODEL 737-8		
MAX DESIGN TAXI WEIGHT	POUNDS	159,900	180,300	182,700
	KILOGRAMS	72,529	81,782	82,871
MAX DESIGN TAKEOFF WEIGHT	POUNDS	159,400	179,800	182,200
	KILOGRAMS	72,302	81,555	82,644
MAX DESIGN LANDING WEIGHT	POUNDS	150,300	150,300	152,800
	KILOGRAMS	68,174	68,174	69,308
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	142,900	142,900	145,400
	KILOGRAMS	64,818	64,818	65,952
SEATING CAPACITY	TWO-CLASS	178	178	178
	SINGLE-CLASS	189	189	189
MAX CARGO VOLUME LOWER DECK	CUBIC FEET	1,540	1,540	1,540
	CUBIC METERS	43.6	43.6	43.6
USABLE FUEL *[1]	US GALLONS	6,820	6,820	6,820
	LITERS	25,817	25,817	25,817
	POUNDS	45,694	45,694	45,694
	KILOGRAMS	20,730	20,730	20,730



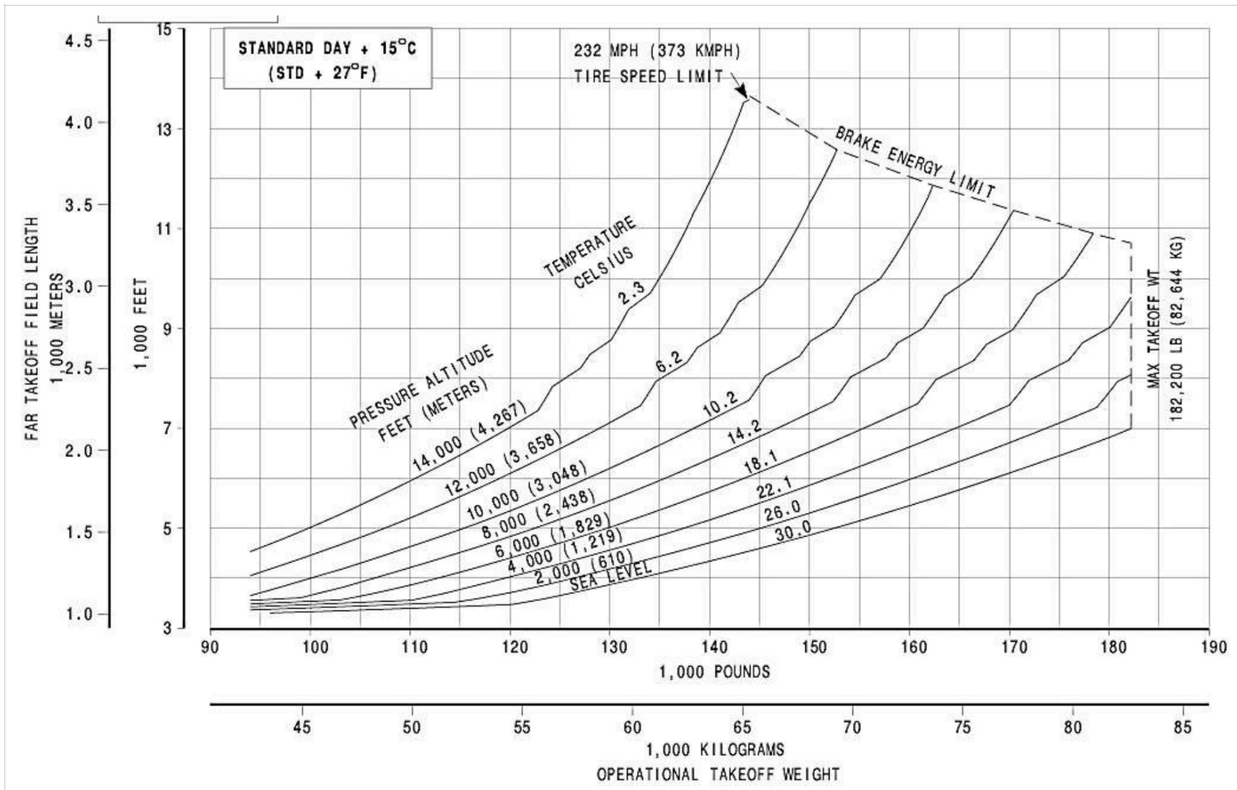


Figure 2. Boeing 737-8 Max Information

Table 2 shows the analysis for Boeing 737-8 Max and the Boeing 737-800.

c) Estimate the average fuel per passenger assuming a load factor of 0.84 (84% of the seats used) for both routes. Can the airline achieve good fuel savings using the new Boeing 737-8 Max compared to the standard Boeing 737-800?

Table 3 shows the analysis for both aircraft using 84% load factor. The airline will save 22% per passenger.

Table 3. Analysis of Boeing 737-8 Max and Boeing 737-800 with 84% Passenger Load.

Parameter	Boeing 737-8 Max	Boeing 737-800
OEW (lbs)	99,000	91,300
MTOGW (lbs)	181,000	174,200
Passenger Seats	162	160
Passenger Load (lbs) at 84%	29,938	29,568
OEW + Payload (lbs)	128,938	120,868
Fuel (lbs)	17,562	21,132
DTW (lbs)	**146,500**	**142,000**
Stage length (nm)	1,100	1,100
Fuel per passenger (lbs)	108	132
Runway Length needed (feet)	**4,700**	**5,300**
Runway length Available	7,169	7,169
SAR (nm/lb)	0.063	0.052

d) Using the Payload-Range diagram of each aircraft, and using the longest flight of the two routes, find the Specific Air Range (SAR) parameter for each aircraft. Comment on the SAR values calculated.

SAR is the distance traveled for each pound of fuel used.

SAR (Boeing 737-8 Max) at full passenger load = 0.057 nm/lbs

SAR (Boeing 737-8 Max) at full passenger load = 0.035 nm/lbs

e) Considering various factors which aircraft is the best for this airline? Explain.

The Boeing 737-8 Max is probably the best choice. Fuel savings and better runway length performance are two important factors that favor the Boeing 737-8 Max. Interestingly, the Boeing 737-8 Max is more expensive than the Boeing 737-800 (~$5.5 million).

Problem 3

a) An airline is evaluating future operations out of Salt Lake City International Airport. The airline is evaluating the Boeing 787-8 (with maximum takeoff weight of 502,500 lbs., Rolls-Royce engines, and mixed class seating configuration) and the Boeing 787-9 (with maximum takeoff weight of 560,000 lbs., Rolls-Royce engines, and mixed class seating configuration) to fly from SLC to various European cities including Madrid (MAD) Spain. In this analysis consider the runway length available at SLC (consult airnav webwite). Use the Climate Explorer website (https://crt-climate-explorer.nemac.org/climate_graphs) to find the mean maximum temperature of the hottest month of the year at SLC Airport to use in the analysis. The airline is considering both dual class Boeing 787 configuration.

For the aircraft in question investigate the following:

a) What is the design temperature at SLC for runway analysis? How does it compared to ISA conditions?

ISA + 43 deg. F conditions.

b) Can the aircraft operate the route SLC-MAD (Madrid) with a 90% passenger load? State the numbers to justify your answer.

Both aircraft can operate with 90% passenger load.

c) Can the aircraft operate the route SLC-CDG with a full passenger load?

The Boeing 787-8 cannot operate with 100% passenger load.

The Boeing 787-9 can operate with 100% passenger load.

d) Find the maximum freight capacity for the SLC-MAD route above the full passenger load. State all your assumptions.

e) What version of the Boeing 787 is best suited for this airline? Explain.

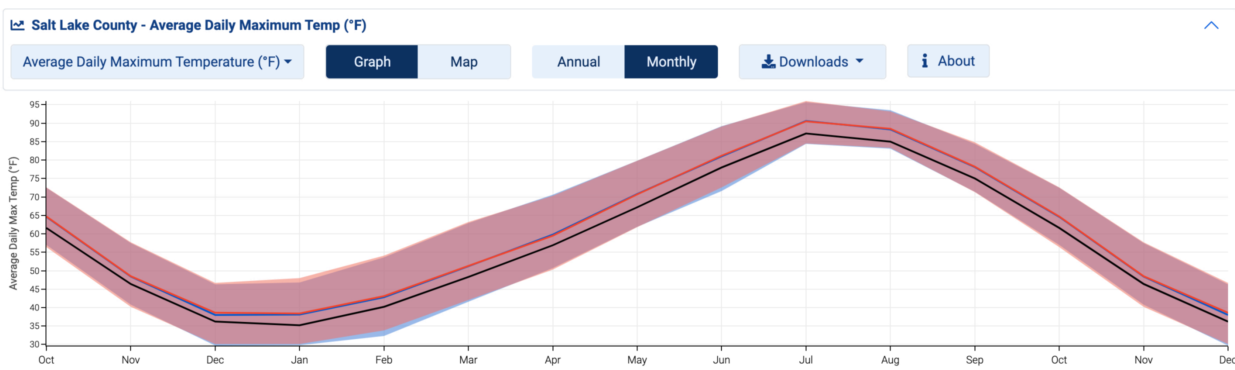
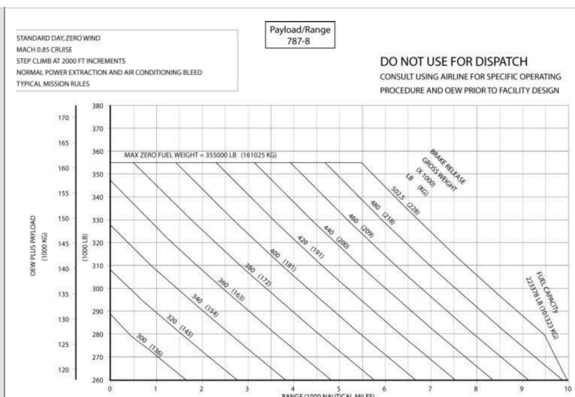


Figure: Temperature Profile for SLC Airport. 87 deg. Fahrenheit is the design temperature. ISA conditions are 44 deg. F at SLC. Hence use ISA + 43 deg. F conditions.

2.1.1 General Characteristics: Model 787-8

CHARACTERISTICS	UNITS	ENGINE MANUFACTURER	
		GENERAL ELECTRIC	ROLLS-ROYCE
MAX DESIGN TAXI WEIGHT	POUNDS	503,500	503,500
	KILOGRAMS	228,383	228,383
MAX DESIGN TAKEOFF WEIGHT	POUNDS	502,500	502,500
	KILOGRAMS	227,930	227,930
MAX DESIGN LANDING WEIGHT	POUNDS	380,000	380,000
	KILOGRAMS	172,365	172,365
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	355,000	355,000
	KILOGRAMS	161,025	161,025
SEATING CAPACITY	ONE CLASS	359 ALL-ECONOMY SEATS; FAA EXIT LIMIT = 381 SEATS	
	MIXED CLASS	242 DUAL-CLASS; 24 BUSINESS CLASS, 218 ECONOMY CLASS (SEE SEC 2.4)	
MAX CARGO - LOWER DECK *[1]	CUBIC FEET	4,826	4,826
	CUBIC METERS	136.7	136.7
USABLE FUEL *[2]	U.S. GALLONS	33,340	33,340
	LITERS	126,206	126,206
	POUNDS	223,378	223,378
	KILOGRAMS	101,343	101,343



Payload/Range for Long-Range Cruise: Model 787-8 (Typical Engines)

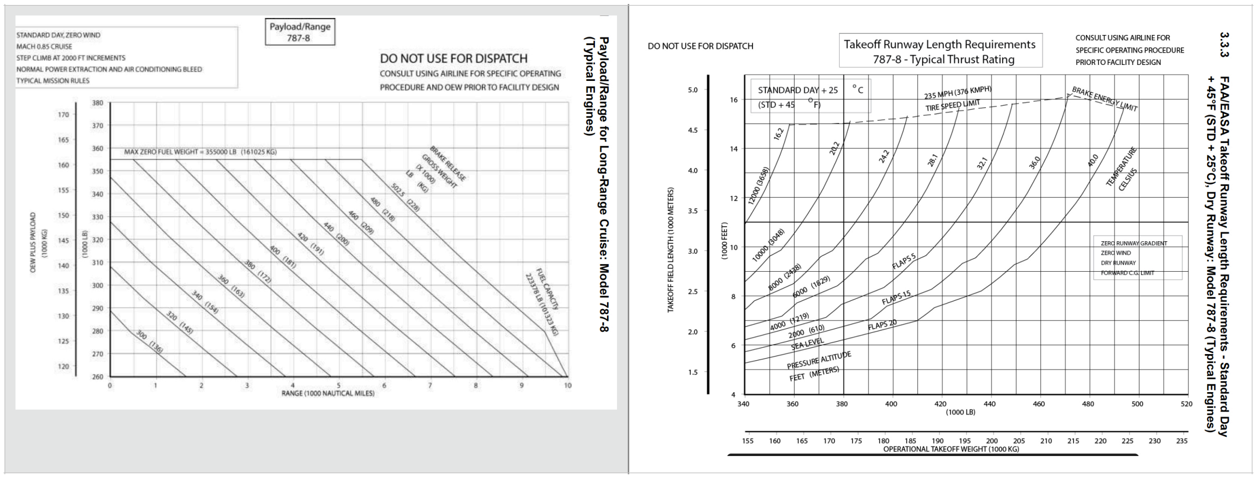


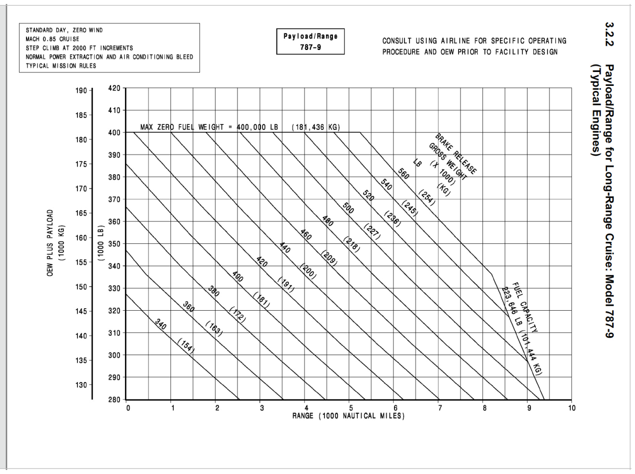
Figure 3. Payload-Range Diagram for Boeing 787-8. Boeing 787-8 Takeoff Field Length. ISA + 45 deg. F.

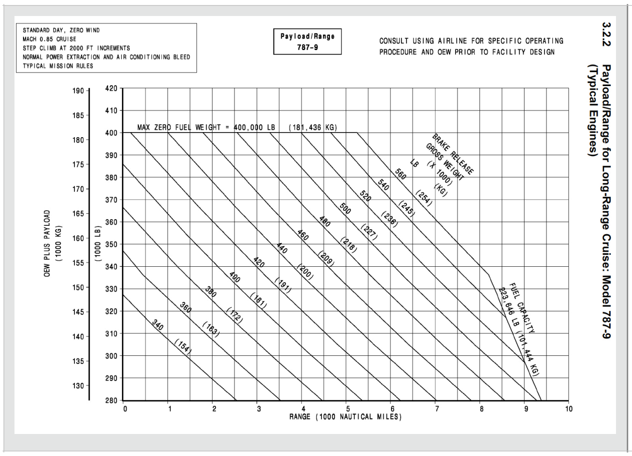
Table 4. Boeing 787-8 Analysis. 90% Passenger Load.

Parameter	Values for Boeing 787-8
OEW (lbs)	260,000
Passenger Load (lbs)	47,916
OEW + Payload (lbs)	307,916
Fuel (lbs)	112,084
DTW (lbs)	420,000
Stage length (nm)	4,850
Fuel per passenger (lbs)	463
Runway Length needed (feet)	11,000
Runway length Available (feet)	12,000

2.1.2 General Characteristics: Model 787-9

CHARACTERISTICS	UNITS	ENGINE MANUFACTURER	
		GENERAL ELECTRIC	ROLLS-ROYCE
MAX DESIGN TAXI WEIGHT	POUNDS	561,500	561,500
	KILOGRAMS	254,692	254,692
MAX DESIGN TAKEOFF WEIGHT	POUNDS	560,000	560,000
	KILOGRAMS	254,011	254,011
MAX DESIGN LANDING WEIGHT	POUNDS	425,000	425,000
	KILOGRAMS	192,776	192,776
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	400,000	400,000
	KILOGRAMS	181,436	181,436
SEATING CAPACITY	ONE CLASS	406 ALL-ECONOMY SEATS; FAA EXIT LIMIT = 420 SEATS	
	MIXED CLASS	290 DUAL-CLASS; 28 BUSINESS CLASS, 262 ECONOMY CLASS (SEE SEC 2.4)	
MAX CARGO - LOWER DECK *[1]	CUBIC FEET	6,090	6,090
	CUBIC METERS	172.4	172.4
USABLE FUEL *[2]	U.S. GALLONS	33,399	33,399
	LITERS	126,429	126,429
	POUNDS	223,773	223,773
	KILOGRAMS	101,522	101,522





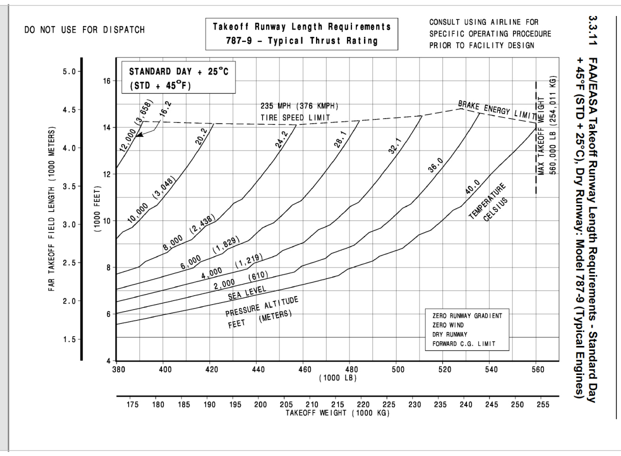


Figure Payload-Range Diagram for Boeing 787-9. Boeing 787-9 Takeoff Field Length. ISA + 45 deg. F.

Table 5. Boeing 787-9 Analysis. 90% Passenger Load.

Parameter	Values for Boeing 787-9
OEW (lbs)	280,000
Passenger Load (lbs)	57,420
OEW + Payload (lbs)	337,420
Fuel (lbs)	117,580
DTW (lbs)	455,000
Stage length (nm)	4,850
Fuel per passenger (lbs)	486
Runway Needed (ft)	9,400
Runway Available (ft)	12,000

Table 6. Boeing 787-8 Analysis. 100% Passenger Load.

Parameter	Values for Boeing 787-8
OEW (lbs)	260,000
Passenger Load (lbs)	53,240
OEW + Payload (lbs)	313,240
Fuel (lbs)	136,760
DTW (lbs)	**450,000**
Stage length (nm)	4,850
Fuel per passenger (lbs)	565
Runway Length needed (feet)	Limited by Tire Speed Limit
Runway length Available (feet)	12,000

Table 7. Boeing 787-9 Analysis. 100% Passenger Load.

Parameter	Values for Boeing 787-9
OEW (lbs)	280,000
Passenger Load (lbs)	63,800
OEW + Payload (lbs)	343,800
Fuel (lbs)	126,200
DTW (lbs)	470,000
Stage length (nm)	4,850
Fuel per passenger (lbs)	521
Runway Needed (ft)	10,000
Runway Available (ft)	12,000

Problem 4

Use the data for the transport aircraft similar to the Boeing 737-800 (http://128.173.204.63/courses/cee5614/cee5614_pub/Boeing737800Jet_class.m) to answer the following questions.

a) Calculate total drag produced by the 76,000 kilogram aircraft during a climb profile with an Indicated Airspeed of 250 knots at 3000 meters above mean sea level conditions. Assume atmospheric conditions to be ISA.

True airspeed (knots) : 279

Altitude (m) : 3,000

Thrust (N) : 141052

Drag (N) : 41409

Aircraft Mass (kg) : 76,000

Rate of climb (m/s) : 19.2

Rate of climb (ft/min) : 3,771

b) Repeat the process when the aircraft is climbing at 9,000 meters and an indicated airspeed of 280 knots.

True airspeed (knots) : 393

Altitude (m) : 9,000

Thrust (N) : 60632

Drag (N) : 41407

Aircraft Mass (kg) : 76,000

Rate of climb (m/s) : 5.2

Rate of climb (ft/min) : 1025

c) Estimate the instantaneous fuel consumption for each flight condition given in parts (a) and (b).

Fuel flow at 3000 meters = 26.8 N/s (2.73 kg/s)

Fuel flow at 9000 meters = 11.5 N/s (1.18 kg/s)