Aircraft Initial Weight Estimation

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1 Introduction

This report is focussed on finding a Class 1 Weight Estimation for an aircraft that fits a set of predetermined requirements. The methodology used to evaluate such an estimation will be clearly outlined and explained with a focus on using realistic data obtained from trusted texts and existing aircraft configurations.

Several assumptions are required to complete this part of the design process. Each assumption needs to be carefully considered and its overall effect and contribution on the final value accounted for. The main reference for the validity of these assumptions will be an initial investigative study that will locate and collect relevant data from aircraft with similar configurations as the design aircraft. Referring to this data will allow this report to stay true to existing and proven designs.

The overall error and accuracy of the method is considered and both final and intermediate values (where possible) are compared against the existing aircraft to assess the validity of the results. This way the method is not considered in a vacuum but instead the short comings and benefits of the approach can be seen and learned from.

2 Requirements

Table 1: Design requirements outline

Restriction/Condition	*Description*
Payload	At least *75* passengers, 2 pilot
Range (nm)	At least 1250 nm + standard reserves
Altitude	At least 30,000 ft for design mission
Cruise Speed (kts)	At least 275 kts
Take-off Field Length	FAR 25 field length at most 7,000 ft, at 5000 ft altitude and standard day
Landing Distance	FAR 25 field length at most 5,000 ft, standard day, $W_L > 0.95\ W_{TO}$
Climb	Climb to 25,000 ft in at least 20 min
Service Ceiling	At least 35,000 ft
Certification Standard	FAR 25

Outlined above are the design requirements. Most relevant for the following report are the range, payload and Cruise speed. Using these requirements, FAA standards and design data from comparable aircraft a set of assumptions can be produced that should allow for the accurate estimation of the Maximum Take-off weight for an aircraft that meets the requirements outlined in **Table [1]**.

3 Assumptions

3.1 Crew, Cargo and Passengers

In order to correctly gauge the payload weight for the design the composition of individuals found on the aircraft must be accounted for. This involves the consideration of gender, age and role. Fortunately, the FAA provides guidelines and standards that can be used to assess the contribution humans have regarding the aircrafts weight. This includes baggage, carry-on and personal items.

Based on the requirements at least 75 passengers must be considered and two pilots. FAA requires 2 flight attendants be present for flights carrying more than 50 but less than 101 passengers.

The FAA recommends assuming a 50% gender split where no gender is specified. It also points to CDC data for standard weights and states an adjustment of 5 lbs in the summer and 10 lbs in the winter should be added to account for clothing variation.

The same applies to crew but a uniform weight should be considered instead of seasonal clothing.

Regarding cargo and luggage, the FAA recommends conducting a survey. For our purposes each passenger's carry-on luggage and personal item weight is assumed to be 16 lbs as per FAA regulations. A heavy bag is regarded as 50 lbs so that is the standard weight considered for checked luggage.

Table 2: Standard Passenger, Crew and Cargo weights with totals [8] [9] [10]

Type	*Weight (lbs)*	*Amount*	*Totals (lbs)*
Male	200	37.5	7500
Female	170	37.5	6375
Winter Clothing	10	75	750
Crew (inc. uniform)	190	4	760
Baggage (Carry on + Checked)	66	75	4950

2.2 Aircraft Values and Properties

In order to choose relevant values for use in calculating the Maximum Take Off Weight (MTOW) similar aircraft that were comparable with the design specification had to be selected. Considering these aircraft meant relevant design variables and properties could be used when evaluating MTOW.

To ensure accuracy the chosen aircraft had to match elements of the requirements within reason. A focus was placed on ensuring the class, range and cruise speed of the aircraft were similar. The remaining requirements were a secondary consideration as they had less of an effect on the MTOW calculation. These requirements (ceiling, climb rate, take-off, etc) would of course be important as an indicator for the aircrafts potential performance capabilities – something that would be considered in the next stage of the design process – so were matched where possible.

Three aircraft were considered. These were the Boeing 727-100, Boeing 737-100 and the Airbus A321. The relevant design data is outlined below in **Table [3]** discussion of the relevant detail continues afterwards.

Table 3: Major Design Details/Data for Comparative Aircraft

Aircraft	*Boeing 727-100 [3][2]*	*Boeing 737-100 [5] [1]*	*Airbus A321 [4]*
Range (nm)	2250	1540	3200
MTOW (kg)	76,700	50,000	93,000
Take-off Distance (ft)	8300	6099	
Service Ceiling (ft)	42,000	37,000	29,800
Cruise Speed (kts)	430-473	495-518	450
Passenger Capacity	85-103	106-125	185-220
Engine Type	Low Bypass Turbofan	Low Bypass Turbofan	High Bypass Turbofan
Thrust/Power (kN)	62 - 64	62	133 - 142
Fuel Capacity (L)	29,069	17,900	24,000 – 30,030
Empty Weight (kg)	36,560	25,878	48,500

The values that need to be chosen before MTOW can be calculated are as follows: Specific Fuel Consumption, CL/CD, Empty Weight Variables (a & c), Propeller Efficiency (for prop-based aircraft), the mission segments and the fuel to weight ratios for each segment.

Values for all the above can be approximated using historical data that is dependent on the macro configuration of the aircraft.

Based on the comparison study the aircraft configuration is assumed as follows: Employs a Low Bypass Turbofan engine, which also means propeller efficiency is not required. Values of a and c are derived assuming a Jet Transport Aircraft. Has a straightforward set of mission segments consisting of take-off, climb, cruise, descent and landing. The respective fuel to weight ratio values are typical for their respective flight configurations except for in cruise which is evaluated using the Breguet range equation (jet version).

Table 4: Typical average segment weight fractions [6, pp. 102]

No.	*Mission Segment*	*Fuel to Weight Ratio*
1	Taxi and take-off	0.98
2	Climb	0.97
3	Descent	0.99
4	Approach and landing	0.997

Table 5: The typical maximum lift-to-drag ratio for several aircraft [6, pp. 104]

No.	*Aircraft Type*	*(L/D) max*
1	Sailplane (glider)	20-35
2	Jet Transport	12-20
3	GA	10-15
4	Subsonic military	8-11
5	Supersonic fighter	5-8
6	Helicopter	2-4
7	Home-built	6-14
8	Ultralight	8-15

Table 6: Typical values of SFC for various engines [6, pp. 109]

No.	*Engine type*	*SFC in cruise*	*Units*
1	Turbojet	0.9	lb/h/lb
2	Low-bypass ratio turbofan	0.7	lb/h/lb
3	High-bypass ratio turbofan	0.4	lb/h/lb
4	Turboprop	0.5-0.8	lb/h/hp
5	Piston (fixed pitch)	0.4-0.8	lb/h/hp
6	Piston (variable pitch)	0.4-0.8	lb/h/hp

Using the data from **Tables [6, 5]** we can construct an initial set of values that can be used to estimate the MTOW for the design.

Table 7: Summary of Relevant MTOW Assumptions

Property	*Value*	*Units*
SFC	0.7	lb/h/lb
a	1.02 [7]	
c	-0.06 [7]	
CL/CD	15	

The final value needed is the fuel/weight ratio for the cruise mission segment. Using the Breguet range equation and rearranging it to find F/W gives:

$$\frac{W_e}{W_i} = e^{-\frac{R \cdot SFC}{V \cdot \frac{C_L}{C_D}}}$$

First, we ensure the use of standard units, converting range, velocity and SFC to SI Units.

Table 8: Properties for Breguet range and conversion to SI Units

Property	*Non-SI*	*Units*	*SI*	*Units*
Specific Fuel Consumption	0.7	lb/h/lb	1.9445 x 10^{-4}	kg/Ws [6, pp. 108]
Range	1250	nm	2315000	m
Cruise Velocity	275	kts	141.47	m/s

Substituting these values into the Breguet range equation gives [6, pp. 106]:

$$\frac{W_e}{W_i} = e^{-\frac{2315000 \cdot 1.9445 \times 10^{-4}}{141.47 \cdot 15}} = 0.809$$

Finally, we calculate the Take-off Weight to Fuel ratio [6, pp. 100-102]:

$$\frac{W_{fuel}}{W_{TO}} = 1 - \frac{W_F}{W_{Tax \quad take-off}} \cdot \frac{W_F}{W_{Climb}} \cdot \frac{W_F}{W_{Cruise}} \cdot \frac{W_F}{W_{Descent}} \cdot \frac{W_F}{W_{Approach+Landing}} \cdot (1 + Reserve\ Fuel\ \%)$$

$$\frac{W_{fuel}}{W_{TO}} = 1 - 0.98 \cdot 0.97 \cdot 0.809 \cdot 0.99 \cdot 0.997 \cdot (1 + 0.25) = 0.301$$

4 Calculating MTOW

Using these assumptions, we can now calculate MTOW and compare our calculation against the existing aircraft data presented in **Table [3]** to assess accuracy and ensure our approach and method is valid.

Maximum take-off Weight is the combined weight contribution from all significant sources. The weights considered are:

- Empty Weight (the contribution from the structure and components)
- Crew Weight
- Payload Weight (combined contribution of the cargo, passengers and luggage)
- Fuel Weight

The sum of these weights gives us the MTOW for our design and is a fixed value that is useful in later design stages.

The Fuel and Empty weight are dependant on the Take-off weight. We consider this and write the summation out as follows [7]:

$$W_{TO} = W_{crew} + W_{payload} + \left(\frac{W_{fuel}}{W_{TO}}\right) W_{TO} + \left(\frac{W_{empty}}{W_{To}}\right) W_{TO}$$

The fuel/take-off ratio was evaluated in section 3 and came out as 0.301, the Empty/take-off ratio can be estimated with the below equation [7]:

$$\frac{W_{empty}}{W_{TO}} = aW_{TO}^{c}$$

Where a and c were derived in section 3 as values specific to a Jet Transport aircraft and were respectively 1.02 and -0.06.

Using excel to represent the above equations, we can solve for W_{TO} iteratively. After a few iterations the results are outlined in the below table:

Table 9: Iteratively solved weight values

Weight	*Value*	*Units*
W_{TO}	107251.3	lb
W_{Empty}	54598.21	lb
W_{Fuel}	32318.03	lb
$W_{Payload}$	20335	lb

So, this gives a derived value for MTOW at **107251** *lbs* for the given design requirements.

5 Discussion and Accuracy

Table 10: Relevant reference data referred to in the discussion. Data converted to ensure similar units.

Aircraft	*Boeing 727-100 [3]*	*Boeing 737-100 [5]*	*Airbus A321 [4]*	*Design*
Range (nm)	2250	1540	3200	1250
MTOW (kg)	76,700	50,000	93,000	48,648
Take-off Distance (ft)	8300	6099		7000
Service Ceiling (ft)	42,000	37,000	29,800	35000
Cruise Speed (kts)	430-473	495-518	450	275
Passenger Capacity	85-103	106-125	185-220	80
Engine Type	Low Bypass Turbofan	Low Bypass Turbofan	High Bypass Turbofan	Low Bypass Turbofan
Thrust/Power (kN)	62 - 64	62	133 - 142	
Fuel Capacity (L)	29,069	17,900	24,000 – 30,030	
Empty Weight (kg)	36,560 [2]	25,878 [1]	48,500	24,765

Direct comparison between other aircraft design data and the calculated design data shows a lot of similarities and reasonable values. The closest matching aircraft is the Boeing 737-100. The 737 most was the closest to the required design values and of note has the most similar range. This range similarity is the major contributing factor explaining the similar configurations. Range has the most prominent effect on the amount of fuel required which subsequently makes up a large portion of the weight and is the most variable weight component. The passenger numbers aren't likely to change dramatically and don't contribute as heavily to the overall weight.

The largest notable deviations from the design requirements and the selected aircraft are cruise velocity and range. Both the Airbus and Boeing 727-100 have differing ranges but similar Cruise speeds when compared to the Boeing 737-100 (which matches the data well). As these two aircraft differ rather dramatically from the MTOW value calculated for the design, it seems reasonable to assume the largest contributing factor regarding MTOW is the range, and that the velocity is a minor contributor in comparison.

With that in mind, the last components of this discussion will consider the accuracy of the assumptions that contribute to the range related weight.

The primary values relevant are specific fuel consumption and CL/CD. Regarding SFC this value is dependent on the chosen engines and the respective configuration of these engines. As most aircraft in the FAR 25 Class tend to employ similar configurations – mostly two turbofan engines. Error in this case could result from incorrectly assuming a low bypass option. This option was selected due to the worse performance and so MTOW would be overestimated instead of underestimated ensuring the design will remain safe even if less efficient. The specific engine model itself would also introduce error as the assumed SFC value could differ even between engines of similar design, depending on the manufacturer and mounting decisions.

CL/CD is largely dependent on the aerodynamic performance of the aircraft. Here there is a chance for large variation. In these early stages the aerodynamic surfaces and drag performance are not known. For this reason, empirical data must be used to estimate the potential aerodynamic performance of the final aircraft. This data even for a particular class is given as a range. In this case for a Jet Transport, it is noted as between 12 – 20. Deciding on a value just withing that range can affect the overall accuracy of the MTOW calculation. Attempting to account for things like the number of engines and how aerodynamic the aircraft will be, can help in deciding whether the CL/CD should be chosen from the top or bottom of the range but regardless there is bound to be some error introduced. A lot of complexity is tied up in the CL/CD value that is not calculatable or even realistically knowable in the early design stages, for this reason CL/CD assumptions can introduce significant error into the MTOW calculations.

6 Conclusion

The overall purpose of this report was to perform a class 1 estimation of the aircrafts weight based on realistic requirements and to compare the results with other similarly configured aircraft. The findings and values for MTOW (48,648 lbs) sit within a reasonable range for what would be expected for aircraft following design requirement outlined in **Table [1]**. It is noted that the most accurate match is the Boeing 737-100 which matches the required range the closest. Therefore, it can be deduced that the range has a significant effect on the MTOW's value and so for any future reports correctness and accuracy surrounding range effected weight values (SFC, CL/CD) should be considered critical for obtaining realistic MTOW values. Overall, the report generated a useful MTOW value that can be used in further design phases that would presumably focus more heavily on the other outlined requirements.

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