An Estimation of the Maximum Take-off Weight Commuter Category Aircraft Based on Airstrip Condition on Remote High Terrain Area

L L Sunara¹ and W Nirbito¹,²
¹Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia.
²Corresponding author’s e-mail: wahyu.nirbito@ui.ac.id

Abstract. The conditions of the runway on remote high terrain area with mountain conditions are the problem for the aircraft. The short of runway length and the higher location can affect to the take-off performance of the aircraft. Thus the determination of the maximum take-off weight is critical in order for the aircraft to take-off safely. The purpose of this research is to determine the maximum take-off weight for 19 passengers commuter category and double engine propeller driven aircraft based on runway condition at ISA +20 on remote high terrain area. The intended of runway conditions are the altitude of the runway location, the slope of the runway, the surface condition of the runway and the wind speed around the runway. The take-off distance approach based on aerodynamic characteristics, geometry, and power plant is described. The results obtained that the aircraft can take off at remote high terrain area with an altitude above 5000 feet and runway length of 393 m to 600 m for all engine operative conditions.

1. Introduction

Air transportation is one of the solutions to connect one area with other areas. The remote area with geographical conditions in the mountains is a difficult location to access. The aid of food and health are needed for people in remote areas, therefore the access of the transportation is essential as a bridge to aid delivery. The runway conditions that are located in mountainous areas with an altitude above 5000 feet and there are gaps and valleys such as Papua region in Indonesia is one of the problems. Thus the appropriate calculation is needed for the take-off operations in that area. The maximum take-off weight is important in flight operations because it includes the amount of passengers and fuel that the aircraft can carry. The commuter category with 19 passenger seats and double engine propeller driven aircraft is an aircraft that is still in development stage and aims to operate in remote areas. Thus it is necessary to predict data for the maximum take-off weight on remote areas. At the take-off phase, the aircraft speed is arranged regularly in accordance with the regulation [1]. The regulation uses Civil Aviation Safety Regulation (CASR) part 23 for commuter category aircraft as a reference. The take-off distance approach is used to determine the maximum take-off weight based on runway conditions. There are several terms of take-off distance including take-off distance available (TODA), take-off run available (TORA) and accelerate-stop distance available (ASDA) [2]. Engine failure may occur during the take-off process. if an engine failure occurs, then the pilot must determine whether the aircraft should continue take-off with one of the engine failures or rejected take-off. The maximum
speed at which a pilot decides to rejected take-off when an engine failure occurs is at speed $V_1$. If the engine fails before $V_1$, the pilot can rejected take-off (RTO) and brake until the aircraft stops for the rest of the available runway [2]. The engine failure at the time of take-off process is undesirable. Thus it is necessary to estimate the maximum take-off weight when the engine failure occurs to prevent the accident.

The required distance from the aircraft starts moving to a halt in the rejected take-off condition is ASDA. The required take-off distance for all engine operative (AEO) and continue take-off in case of the engine failure occurs until reach the screen height 35 feet is TODA [1]. Each runway is described by the relevant distances available, referred to as TORA, TODA, and ASDA respectively [2]. Runway conditions such as altitude location, wind velocity around the runway, runway surface conditions and runway slope are some conditions that affect the take-off performance of the aircraft. Knowing the maximum take-off weight (MTOW) for each runway, it can be a reference for a pilot or crew to determine the amount of payload in order to take-off safely on the runway.

2. Methods
The aircraft move following the regulated speed during the take-off process for safety purpose [3]. In the regulation has been set about the speed limits on take-off conditions by considering that the speed is the minimum safe speed.

![Flowchart of calculating process](Image)

**Figure 1.** Flowchart of calculating process

Figure 1 shows the flowchart of calculating process. The take-off distance is calculated using numerical method [4]. The length of distance traveled by aircraft depends on the acceleration of the aircraft in conditions with different altitude, the slope of runway, runway surface conditions, weight and wind speed [1]. On the calculation of take-off distance using 3 weight as a reference, including 4310 kg, 6000 kg and 7030 kg. The weight of 4310 kg is the empty weight of the aircraft without payload. The weight of 7030 is the maximum take-off weight based on design structure limit, while
the weight of 6000 kg is the middleweight between 4310 kg and 7030 kg. Take-off distance is measured using ground speed, therefore the wind speed will affect ground speed \[5, 6\]. The calculation of the take-off distance includes the condition of all engine operative (AEO), one engine inoperative (OEI) and rejected take-off (RTO), where for the case of RTO one of the engines does not operate the same as in the case of OEI. In this calculation, the case of engine failure occurs for the OEI dan RTO condition is the same. Thus the pilot decides whether continue take-off or rejected take-off at \(V_1\) for each case. Acceleration of the aircraft during on the ground refers to the equation below \[5\]:

\[
\frac{d}{dt}[T - \mu R W \cos\theta - (C_D - \mu C_L)qS] - W \sin \theta \tag{1}
\]

The take-off distance data is used to determine the maximum take-off weight. The take-off distance result is take-off distance available (TODA). The result from a numerical calculation is the take-off distance chart. Based on the take-off distance chart there are a curves of the relationship between the required take-off distance with correction factors such as wind speed \((V_w)\), runway slope, runway surface conditions \((S_c)\) and altitude \((Alt)\) of the runway location \[5\]. The multiple regression method with least squares approximation is used to determine the maximum take-off weight equation based on each curve in the take-off distance chart \[4, 7\]. A suitable equation is obtained based on the best fit of the curve. Thus the maximum take-off weight is \(W_{TO} = f(Alt, RL, V_w, Slope, S_c)\). In each case, there are 4 equations with each factor affecting the required take-off distance in determining the maximum take-off weight.

\[
S_1 = f(RL, V_w) \tag{2}
\]
\[
S_2 = f(S_1, Slope) \tag{3}
\]
\[
S_3 = f(S_2, S_c) \tag{4}
\]
\[
W_{TO} = f(S_3, Alt) \tag{5}
\]

The distance of \(S_1\) is the effect of wind speed on the available runway length \((RL)\). \(S_2\) is the distance at \(S_1\) which is affected by the slope of the runway while \(S_3\) is the distance of \(S_2\) which is affected by the runway surface condition. \(W_{TO}\) is the maximum take-off weight with the distance \(S_2\) which is affected by the altitude of the runway. The results of the equations comes from multiple regression methods. Thus the equations for all engine operative conditions are as follows:

\[
S_{1, AEO} = 0.201 + 1.004(RL) + 0.891(V_w) + 0.018(RL)(V_w) \tag{6}
\]
\[
S_{2, AEO} = 0.1197 + 1.003(S_1) + 14.35(Slope) - 0.073(S_1)(Slope) \tag{7}
\]
\[
S_{3, AEO} = -31.84 + 1.145(S_2) + 31.84(S_c) - 0.144(S_2)(S_c) \tag{8}
\]

For the engine failure conditions, there are two cases that is take-off with one engine or rejected take-off. The equations for one engine inoperative (OEI) conditions are as follows:

\[
S_{1, OEI} = 0.167 + 1.002(RL) + 2.608(V_w) + 0.013(RL)(V_w) \tag{9}
\]
\[
S_{2, OEI} = 21.842 + 0.969(S_1) + 30.384(Slope) - 0.116(S_1)(Slope) \tag{10}
\]
\[
S_{3, OEI} = -46.454 + 1.167(S_2) + 46.454(S_c) - 0.167(S_2)(S_c) \tag{11}
\]

The equations for rejected take-off (RTO) conditions are as follows:

\[
S_{1, RTO} = 1.309 + 1.003(RL) + 4.983(V_w) + 0.015(RL)(V_w) \tag{12}
\]
\[
S_{2, RTO} = 2.028 + 0.99(S_1) + 24.225(Slope) - 0.031(S_1)(Slope) \tag{13}
\]
\[
S_{3, RTO} = -70.291 + 1.142(S_2) + 70.291(S_c) - 0.1428(S_2)(S_c) \tag{14}
\]
S₃ is the required take-off distance for a given runway length that has been corrected by wind speed, runway slope and runway surface conditions. In determining the maximum take-off weight using the distance of S₃ which is corrected by the altitude of the runway location. Here are the maximum take-off weight (MTOW) equations for AEO, OEI and RTO conditions in kilogram:

\[
W_{\text{TO-AEO}} = 9774.4 - 9.38 \times 10^6 \left( S_3^{-1.32} \right) - 0.111 (Alt^{1.04}) - 20.861 (S_3^{-1.32})(Alt^{1.04}) \\
W_{\text{TO-OEI}} = 9282.16 - 380816 \left( S_3^{-0.76} \right) - 0.166(Alt^{0.99}) + 1.729(S_3^{-0.76})(Alt^{0.99}) \\
W_{\text{TO-RTO}} = -68038 + 50339(S_3^{-0.06}) + 2.026(Alt^{0.97}) - 1.514(S_3^{-0.06})(Alt^{0.97})
\]

3. Discussion
The airstrip data in the remote area are presented in table 1. The runway conditions include the runway length in meters, altitude of the runway in feet, runway slope in percent and wind speed around the runway in knots. Figure 2 and 3 shows the maximum payload can carry by aircraft for each runway.

Table 1. The maximum take-off weight data for each airstrip on remote area

| Airstrip | RL | ISA | Alt  | Slope | Surface  | Vw  | MTOW   |
|---------|----|-----|------|-------|----------|-----|--------|
|         |    |     |      |       |          |     | AEO    | OEI  | RTO  |
| A       | 600| 20  | 7975 | -4    | Asphalt  | 1   | 7120.54| 5912.34| 4702.80|
| B       | 590| 20  | 6950 | 0     | Asphalt  | 1   | 6823.65| 5596.67| 4923.94|
| C       | 500| 20  | 6227 | -2    | Asphalt  | 1   | 6675.41| 5462.80| 4725.41|
| D       | 415| 20  | 6100 | -2    | Grass    | 1   | 5894.32| 4919.98| 4180.52|
| E       | 444| 20  | 5150 | -7    | Grass    | 1   | 5721.57| 4791.84| 3224.66|
| F       | 393| 20  | 5200 | -1    | Grass    | 1   | 6876.13| 5683.08| 3375.00|
| G       | 500| 20  | 5900 | -6    | Grass    | 1   | 7016.92| 5805.14| 3978.83|

Figure 2. Maximum payload for various airstrip with headwind condition.

Figure 3. Maximum payload for various airstrip with tailwind condition.
The variation of the runway conditions for each runway will affect the take-off distance. Due to the runway length on the remote area is short. Thus if the required take-off distance exceeds the runway length, it will impact the reduction of the weight of the aircraft in order to take-off with the available runway length. The aircraft can operate with the maximum take-off weight over 7030 kg in A airstrip. Because the weight of 7030 kg is the maximum structural limit weight for the aircraft. Thus the aircraft must operate with 7030 kg even though the aircraft can operate over that weight.

The maximum take-off weight on AEO case is greater than OEI and RTO case. This is because when the engine failure occurs, the available thrust only comes from one engine and hence, the take-off distance will be farther for the same weight. The maximum payload for OEI is greater than RTO, therefore determining the maximum take-off weight on OEI condition is preferred for operational purpose. Thus if the engine failure occurs, the aircraft can still take-off safely with one engine fails. Based on the equation for each condition, the results obtained between the effect of the runway condition to the maximum take-off weight are shown in Figures 4 to 7. Figure 4 is the effect of runway altitude to the maximum take-off weight. Increasing altitude of the runway will decrease the maximum take-off weight. This is because in the higher altitude the air density more lowest and thus the required take-off distance will be farther.

**Figure 4.** MTOW vs TODA for variation altitude with AEO condition.

**Figure 5.** MTOW vs TODA for variation slope with AEO condition at 6000 feet.

The effect of the runway slope to the maximum take-off weight is presented in figure 5. In the runway with a downhill condition, the maximum take-off weight will be greater rather than an uphill condition. This is because the down slope will enhance the acceleration of the aircraft during the ground roll phase, and thus the required distance becomes shorter. The effect of wind speed to the maximum take-off weight is presented in figure 6. The direction of the headwind is opposite to the direction of the aircraft motion and it will enhance the relative velocity between the aircraft and the air. The greater of relative velocity between the aircraft and the air will enhance the lift force of the aircraft and the take-off distance becomes shorter. Thus the rest of the available runway length can be used to enhance the weight of the aircraft. Figure 7 represents the effect of the runway surface condition on the maximum take-off weight. The coefficient of rolling between asphalt and grass is different. Asphalt has the rolling coefficient of 0.025 while grass is 0.05. The greater of the rolling coefficient value will decrease the acceleration of the aircraft. Thus the required take-off distance will be farther and impact to reduce of the aircraft weight.
4. Conclusion

The maximum payload with RTO case is lower than OEI case in engine failure condition. There are 5 airstrips that are not possible to rejected take-off (RTO) such as C, D, E, F and G airstrip. The maximum take-off weight on C, D, E, F and G airstrip is below the empty weight of the aircraft for RTO case in engine failure condition. Thus the required take-off distance will exceed the runway length even if the aircraft does not carry any payload. The most critical airstrip is an F airstrip with a maximum take-off weight only 5669.49 kg under headwind conditions and 5478.27 kg under tailwind conditions for AEO conditions. The maximum payload on AEO condition above the empty weight of the aircraft. Thus for normal operation without engine failure occurs, this aircraft can still operate safely at all of the runways.

5. Acknowledgements

The authors would like to thank PITTA grant programme of Universitas Indonesia for funding this research with grant number 2553/UN2.R3.1/HKP.05.00/2018. The authors also grateful to Indonesian Aerospace company for the facilities, guidance, and opportunities in the development of commuter category aircraft in this research.

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