Method for Determining Takeoff Weight and Thrust-To-Weight Ratio of Aircraft Variants by Decision Speed with Engine Failed at Takeoff Run

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Abstract. In modern time the aircraft variants creation is main trend in the aviation industry. One the aspect of the aircraft safety is its safety take-off [1]. The aircraft parameters like relative take-off weight and thrust-to-weight ratio can determine many its performance include take-off. Their influence on decision speed during take-off of modified transport category airplanes are explored. The analytic model is simple and high efficiency way for the first approach of airplane’s safety analyses. The problem is solved by analytics modelling airplane motion on runway during take-off. Quantitative estimation of influence of the airplane weight and thrust-to-weight ratio variation on decision speed of continued or aborted take-off with critical engine failure is given on the base of example of heavy cargo airplane. The application of this way for the airplanes safety analysis is important for each types of aircraft. Estimation model is given in dimensionless parameters and so is applicable for any type of transport category airplanes.

1. Introduction

The development process of modifications is widely used in aircraft engineering [2-12]. In the process of designing modifications are changed to obtain required competitive performance, such as: chart “cargo-distance”, fuel efficiency, cost of a ton-kilometer of air transportation [2,4,13].

The required competitive performance is achieved by changing the basic parameters of modifications such as their relative takeoff weight and takeoff thrust-to-weight ratio relative value [4,11,14].

Changes to these determining parameters affect virtually on all assemblies and systems of modifications, including takeoff and landing characteristics (TOLC), i. e., on takeoff and climb distance and on one of the most important parameters — the decision speed to stop and continue takeoff (Figure 1). The importance of this parameter is determined not only by keeping the modifications’ TOLC close to ones of the basic version of the aircraft, but also by the possibility of aircraft modifications at declared airbases.
2. Objective
To quantify the influence of the changed parameters $\bar{G}_{t.o}$ and $\bar{t}_{o}$ on the value of decision speed $V_1$ during take-off by modelling the movement of the aircraft on the ground.

3. Solving the Problem
At the takeoff run portion the plane moves along the runway (RWY) at a rate from $V_{t.o}=0$ to liftoff speed $V_{lift}$.

When calculating the takeoff run [12,15] we assume that this procedure is performed by using main landing gear. Angle of attack ($\alpha_{t.o}$) and thrust turning angle ($\varphi_T$) in the process of takeoff are considered constant that allows to accept $\alpha_{t.o} - \varphi_T \approx 0$, and $\cos(\alpha_{t.o} + \varphi_T) \approx 0$, and $\sin(\alpha_{t.o} + \varphi_T) \approx 0$.

Integral equation of takeoff run length with the assumptions accepted is as follows:

$$L_{t.o} = \frac{1}{2g} \int_0^V \frac{dV^2}{K_{1_{t.o}} - f_{wheel} - \rho_0 S_w V^2 / 2G_{t.o}} (C_{D_{t.o}} - f_{wheel} C_{L_{t.o}})$$

where $V_{lift}$ is liftoff speed; $K_1$ is factor considering the engine thrust decay by speed and loss in air intakes; $t_{t.o}$ is thrust-to-weight ratio; $f_{wheel}$ is coefficient of rolling friction; $\rho_0$ is air density at 0 km altitude; $S_w$ is full wing area; $G_{t.o}$ is takeoff weight of airplane; $C_{D_{t.o}}$ is drag ratio at takeoff; $C_{L_{t.o}}$ is lift ratio at takeoff.

The integration is carried out graphically from $V_{t.o}=0$ to

$$V_{lift} = \sqrt{\frac{2G_{t.o}}{\rho_0 C_{L_{t.o}} S_w}}.$$
\[ L \approx \frac{V_{\text{lift}}^2}{2g \left( K_{t, o} - f_{\text{wheel}} - \frac{\rho_0 C_{\text{Dr}, o} S_w V_{\text{lift}}^2}{6G_{t, o}} \right)} \]  

(3)

where \( K_1 \) is a factor considering the engine thrust decay by speed and loss in air intakes.

For turbojet engines with the standard atmosphere \( K_1 \approx 0.9 \) for \( T_0 = +30^\circ \text{C} \) and 730 Hg mm \( K_1 \approx 0.813 \); \( f_{\text{wheel}} \) is coefficient of rolling friction \( 0.02 \leq f_{\text{wheel}} \leq 0.08 \), 0.02 – on dry concrete, 0.04 – on hard solid; \( C_{\text{Dr}, o} \) is drag coefficient during takeoff run.

If reference and modified airplane takeoff lengths are equal \( L_{t, o} = L_{t, o} / L_{t, o, b} = 1 \) and \( K_1, f_{\text{wheel}}, \rho_0, C_{\text{Dr}, o}, C_{\text{Lift}}, S_w \) are constants, we have an equation

\[ \frac{1}{K_{t, o} - f_{\text{wheel}} - \frac{\rho_0 C_{\text{Dr}, o} S_w V_{\text{lift}}^2}{6G_{t, o}} = \frac{V_{\text{lift}}^2}{K_{t, o} - f_{\text{wheel}} - \frac{\rho_0 C_{\text{Dr}, o} S_w V_{\text{lift}}^2}{6G_{t, o}}}} \]

(4)

Substituting the expression \( V_{\text{lift}, b}^2, V_{\text{lift}}^2 \) from (2), we get an equation to assess mass variation of potential modifications

\[ G_{t, o} = \frac{K_1}{f_{\text{wheel}} + C_{\text{Dr}, o} / 3C_{\text{Lift}} - f_{\text{wheel}} - \frac{\rho_0 C_{\text{Dr}, o} S_w V_{\text{lift}}^2}{6G_{t, o}} - 1} \]

(5)

Decision speed \( (V_1) \) at takeoff run should ensure the safe termination or continuation of the takeoff with a critical engine failed [9,18-20].

Rejected takeoff distance \( (L_{\text{RTOD}} \leq L_{\text{ASDA}}) \) and required distance of complete takeoff run \( (L_{\text{RDCTO}} \leq L_{\text{ATOOR}}) \) are respectively equal:

\[ L_{\text{ASDA}} \geq L_{\text{RTOD}} = L_{0 \rightarrow V_{\text{fail}}} + L_{V_{\text{fail}} \rightarrow V} + L_{V_{\text{fail}} \rightarrow V_{\text{lift}}} \]

\[ L_{\text{ATOOR}} \geq L_{\text{RDCTO}} = L_{0 \rightarrow V_{\text{fail}}} + L_{V_{\text{fail}} \rightarrow V} + L_{V_{\text{fail}} \rightarrow V_{\text{lift}}} \]

(6)

(7)

where \( L_{0 \rightarrow V_{\text{fail}}} \) is takeoff run length with all operative engines from start to the moment of critical engine failure at speed of \( V_{\text{fail}} \); \( L_{V_{\text{fail}} \rightarrow V} \) is takeoff run length with one non-operative engine and with standard operation of the rest up to getting the decision speed; \( L_{V_{\text{fail}} \rightarrow V} \) is deceleration segment with non-operative engine from speed \( V_1 \), up to full stop; \( L_{V_{\text{fail}} \rightarrow V_{\text{lift}}} \) is takeoff run length with one non-operative engine and with standard operation of the rest from speed \( V_1 \), up to liftoff speed \( V_{\text{fail}} \).

To determine \( V_1 \) it is required to equal the available rejected takeoff distance (6), reduced by runway overrun length \( (L_{\text{STPWY}}) \) to the required complete takeoff run distance (7) we get

\[ L_{V \rightarrow V_{\text{lift}}} = L_{V \rightarrow V_{\text{lift}}} - L_{\text{STPWY}} \]

(8)

With the accepted assumptions we get fairly accurate analytical expression by using integral equation (1).
\begin{equation}
\frac{V_{lp}^2 - V_1^2}{2q \left[ K_1 \left( 1 - \frac{1}{n_{eng}} \right) t_{r,o} - f_{w,red} - \rho_0 C_{D,w} S_w \left( \frac{V_{lp}^2 - V_1^2}{V_{lp} - V_1} \right) \right] = K_2 \frac{V_1^2}{L_{STPWY}} .}
\end{equation}

where \( n_{eng} \) is quantity of engines; \( C_{D,w} \) is drag coefficient during takeoff run; \( K_2 \) is coefficient that takes into account the decision time required for a pilot and the time of engagement of braking devices of aircraft; \( r_f \) is thrust reverser to engine forward thrust ratio; \( f_{w,red} \) is reduced friction ratio of wheels during takeoff run (mean value).

\begin{equation}
f_{red,weel} = \theta \left[ \frac{i_{NLG} f_{fr} + i_{MLG} f_2}{1 + h_{LG} (f_{fr} - f_2)} \right],
\end{equation}

where \( \theta = 0.75 - 0.95 \) is coefficient depending on the quality (in particular, the inertia) of anti-skid device of main landing gear wheels. With nose brake wheels \( f_{red,weel} = \theta \cdot f_{fr} \); \( f_{fr} \) is friction coefficient of the main landing gear braked wheels, \( f_{fr} = (V, \text{ RWY coating}) \); \( \bar{T}_{NLG} = l_{NLG} / l_{LG} \), \( \bar{T}_{MLG} = l_{MLG} / l_{LG} \), \( \bar{h}_{LG} = h_{LG} / l_{LG} \) are relative linear dimensions (to wheel base \( l \)) of nose \( l_{NLG} \) and main \( l_{MLG} \) landing gear offset from aircraft CG, \( h_{LG} \) is linear dimension of aircraft CG from RWY plane.

Let us transform the equation (9) in relative values and get the equation (11).

The equation (11) helps to estimate the relative decision speed dependence on takeoff weight relative increase and relative weight-to-thrust of aircraft potential modifications.

Rejected takeoff is performed as standard one up to the moment of failure of critical engine or aircraft systems influencing the takeoff performance. On taking the decision by the pilot the takeoff is rejected and the aircraft is braked up to full stop [5,9,19,21,22]

\begin{equation}
\bar{T}_{r,o} = \frac{t_{r,o}}{t_{r,b}}, \quad \bar{V}_{lp}^2 = \frac{V_{lp}^2}{V_{lp,b}^2} = \bar{G}_{r,o} = \frac{G_{r,o}}{G_{r,b}}, \quad \bar{V}_1 = \frac{V_1}{V_{lb}}.
\end{equation}

\begin{align}
\frac{V_{lp,b}^2 \bar{G}_{r,o} - V_{lb}^2}{2q \left[ K_1 \left( 1 - \frac{1}{n_{eng}} \right) t_{r,b} + f_{w,red} - \rho_0 C_{D,w} S_w \left( \frac{V_{lp,b}^2 - V_{lb}^2}{V_{lp,b} - V_{lb}} \right) \right] = K_2 \frac{V_{lb}^2}{L_{STPWY}} \quad \tag{11}
\end{align}

Known, quite accurate analytical equation for determination of rejected takeoff distance is as follows [9,18,19]:

\begin{equation}
L = \frac{V_1^2}{2g} \left[ K_{t,r,o} - f_{w,red} - \rho_0 C_{D,w} S_w V_1 \right] + \frac{K_2}{K_{t,r,o} - f_{w,red} - \rho_0 C_{D,w} S_w V_1} \left( \frac{1}{K_1} \left( 1 - \frac{1}{n_{eng}} \right) t_{r,o} + f_{w,red} + \rho_0 C_{D,w} S_w V_1^2 \right) .
\end{equation}

We transform the equation (12) in relative values \( \bar{t}_{r,o} \), \( \bar{G}_{r,o}, \bar{V}_1 \) and under condition when \( \bar{L}_{reg,b} = L_{reg} / L_{reg,b} = 1 \).
\[ L_{\text{rej},b} = \frac{V_{\text{lb}}^2 V_1^2}{2g} \times \left( \frac{1}{K_{t_{1,o,b}^o}}, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_b}, + \left( K_1 \left( 1 - \frac{1}{n_{\text{eng}}} \right) \right) + f_{\text{weed},w} + \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}} \right). \] (13)

We substitute the second additive component in equation (13) from equation (11), and get relationship of three relative values

\[ L_{\text{rej},b} = \frac{1}{2g} \left[ \frac{V_{\text{lb}}^2 V_1^2}{K_{t_{1,o,b}^o}^2, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}} V_{\text{lb}}^2 V_t^2 + V_{\text{lb}} V_{\text{lb},b} V_1 \sqrt{G_{t_{1,o,b}^o} + V_{\text{lb}}^2 V_t^2}} \right] + \frac{V_{\text{lb}}^2 V_t^2}{K_{t_{1,o,b}^o}, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}} V_{\text{lb}}^2 V_t^2} + 2qL_{\text{STRPWY}}. \] (14)

From relationship (14) it is simple to express \( \bar{t}_{1,o} = f \left( \bar{G}_{t_{1,o}^o}, \bar{V}_1 \right) \).

We introduce the following designations:

\[ \alpha_1 = f_{\text{weed}} + \frac{1}{3} \frac{C_{D,\text{a},w} V_{\text{lb}}^2}{C_{\text{lift},b} V_{\text{lb}}^2, G_{t_{1,o}^o}} \] (15)

\[ \alpha_2 = \alpha_1 + \frac{1}{3} \frac{C_{D,\text{a},w} V_{\text{lb}}^2}{C_{\text{lift},b} V_{\text{lb}}^2, G_{t_{1,o}^o}} \] (16)

We substitute \( \alpha_1 \) and \( \alpha_2 \) into equation (14), and get relationship relative \( \bar{t}_{1,o} \).

\[ 2g \left( L_{\text{rej},b} - L_{\text{STRPWY}} \right) = \frac{V_{\text{lb}} \bar{V}_1}{K_{t_{1,o,b}^o}, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}} V_{\text{lb}}^2 V_t^2 + V_{\text{lb}} V_{\text{lb},b} V_1 \sqrt{G_{t_{1,o,b}^o} + V_{\text{lb}}^2 V_t^2}} \right] + \frac{V_{\text{lb}}^2 V_t^2}{K_{t_{1,o,b}^o}, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}} V_{\text{lb}}^2 V_t^2} + 2qL_{\text{STRPWY}}. \] (17)

\[ \bar{t}_{1,o} = -\frac{2g \left( L_{\text{rej},b} - L_{\text{STRPWY}} \right) \left( \alpha_1 - \frac{\alpha_1}{n_{\text{eng}}} + \frac{\alpha_2}{n_{\text{eng}}} \right)}{K_{t_{1,o,b}^o}, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}}} + \frac{V_{\text{lb}}^2 V_t^2}{n_{\text{eng}}} + V_{\text{lb},b} V_1 \sqrt{G_{t_{1,o,b}^o} + V_{\text{lb}}^2 V_t^2} + 2g \left( L_{\text{rej},b} - L_{\text{STRPWY}} \right) \left( \alpha_1 - \frac{\alpha_1}{n_{\text{eng}}} + \frac{\alpha_2}{n_{\text{eng}}} \right) \right] + \frac{V_{\text{lb}}^2 V_t^2}{K_{t_{1,o,b}^o}, f_{\text{weed}} - \frac{\rho_0 C_{D,\text{a},w} V_{\text{lb}}^2}{6G_{t_{1,o,b}^o} G_{t_{1,o,b}^o}}} = 0. \] (18)

To analyze the relationship (18) let us consider as an example the basic version of the aircraft having the following parameters: \( G_{t_{1,o,b}} = 300 \, 000 \, \text{kg}; \, S_o = 600 \, \text{m}^2; \, n_{\text{eng}} = 4; \, t_{1,o,b} = 0.30; \, K_1 \approx 0.813; \, r_f = 0.4; \)
\( g = 9.81 \, \text{m/s}^2; \) \( f_{\text{weel}} = 0.02; \) \( f_{\text{red,weel}} = 0.25; \) \( L_{\text{tip,b}} = 1263 \, \text{m}; \) \( C_{D\text{r.o}} = 0.08; \) \( C_{D\text{red}} = 0.30; \) \( C_{D\text{tip}} = 1.70; \) \( L_{\text{reg,b}} = 1716 \, \text{m}; \) \( L_{\text{STRWY}} = 300 \, \text{m}; \) \( V_{\text{tip,b}} = 65 \, \text{m/s} \) \((234 \, \text{km/h}); \) \( V_{\text{tip,b}} = 71.828 \, \text{m/s} \) \((258.581 \, \text{km/h}). \) Let us note that parameters of the aircraft basic version correspond to equations \((2), (9), (10)\) and \((12).\)

We substitute the values of parameters of the basic version into equation \((18):\)

\[
\alpha_1 = 0.02 + 0.0128457 \frac{V_1^2}{G_{t,o}};
\]

\[
\alpha_2 = 0.0356862 + 0.0128457 \frac{V_1^2}{G_{t,o}} + 0.0156862 \frac{V_1}{\sqrt{G_{t,o}}};
\]

\[
\alpha_2 - \alpha_1 = 0.0156862 + 0.0141951 \frac{V_1}{\sqrt{G_{t,o}}};
\]

\[
\alpha_1 + \frac{\alpha_1}{n_{\text{eng}}} + \alpha_2 = 0.0506862 + 0.0141957 \frac{V_1}{\sqrt{G_{t,o}}};
\]

\[
\alpha_1 \alpha_2 = 10^{-7}(7137.24 + 2839.14 \frac{V_1}{\sqrt{G_{t,o}}} + 7153.2821 \frac{V_1^2}{G_{t,o}} + 1823.537 \frac{V_1^3}{G_{t,o}^2} + 1650.12 \frac{V_1^4}{G_{t,o}^3});
\]

\[
2g \left( L_{\text{reg,b}} - L_{\text{STRWY}} \right) = 277.92 \, \text{m}^2/\text{s}^2;
\]

\[
2g \left( L_{\text{reg,b}} - L_{\text{STRWY}} \right) K_1 \left( 1 - \frac{1}{n_{\text{eng}}} \right) t_{o,b} = 5082.0075 \, \text{m}^2/\text{s}^2;
\]

\[
2g \left( L_{\text{reg,b}} - L_{\text{STRWY}} \right) K_2 \left( 1 - \frac{1}{n_{\text{eng}}} \right) t_{o,b}^2 = 1239.5014 \, \text{m}^2/\text{s}^2;
\]

\[
\frac{V_{\text{tip,b}}^2}{n_{\text{eng}}} = 1056.25 \, \text{m}^2/\text{s}^2; \quad V_{\text{tip,b}}^2 = 4225 \, \text{m}^2/\text{s}^2; \quad V_{\text{tip,b}}^2 = 5159.2615 \, \text{m}^2/\text{s}^2.
\]

After such substitution of parameters of the basic version and their approximation to the third sign we get the following values:

\[
\bar{f}_{t,o}^2 = (0.277 + 0.077) \frac{\bar{V}_1}{\sqrt{G_{t,o}}} + 0.123 \frac{V_1^2}{G_{t,o}} - 0.208 \bar{V}_1^2 + 1.015 \bar{G}_{t,o} \bar{V}_1 + 0.016 + 0.006 \frac{\bar{V}_1}{\sqrt{G_{t,o}}} + 0.016 \frac{V_1^3}{G_{t,o}^2} + 0.004 \frac{\bar{V}_1^4}{G_{t,o}^3} + 0.107 \bar{V}_1^2 + 0.048 \frac{V_1^3}{G_{t,o}^2} + 0.083 \bar{G}_{t,o} = 0. \quad (19)
\]

When substituting the values \( \bar{G}_{t,o} = 1 \) and \( \bar{V}_1 = 1 \) into \((19),\) we get: \( \bar{f}_{t,o}^2 - 1.284 \bar{G}_{t,o} + 0.284 = 0, \) that confirms the correctness of the equation \((19).\)

Let us represent the relationship \((19)\) in graphic form for values \( \bar{V}_1 = 0; 0.5; 0.8; 0.9; 1.0; 1.1; 1.2 \) and \( 1.3 \) if \( \bar{G}_{t,o} = 0.4; 0.5; 0.6; 0.7; 0.8; 0.9; 1.0; 1.1; 1.2; 1.3 \) and \( 1.4. \) (see Figure 2).

Also, the relationship \((5)\) is shown in Figure 2 if \( f_{\text{weel}} = 0.02 \) and \( K_1 = 0.813 \) (dot-dash line).
Selected zone (1-2-3-4-5-1) of the relationship $\tilde{t}_{t,o} = f(\tilde{G}_{t,o}, \tilde{V})$ at $\tilde{L}_{ref} \cong 1.0$ is determined by the following restrictions (boundary conditions):

1. Line 1-2 — by restriction from conditions of probable aircraft operation. For example, decrease of the takeoff weight of the aircraft basic version due to partial fueling or payload. In that case we accept restriction $\tilde{G}_{t,o, min} = 0.78$, i.e. $G_{t,o, min} = 234$ t instead of $G_{t,o} = 300$ t.

2. Line 2-3 — by restriction $\tilde{V}_1 = 0$.

Equation (19) is transformed into relationship

\[
\tilde{G}_{t,o} = 0.985\tilde{t}_{t,o} - 0.192, \tag{20}
\]
which can be considered as completed takeoff run with one failed critical engine at takeoff.

In considered example the required distance of complete takeoff run is equal to 
\[ L = L_{reg} - L_{STP} = 1716 - 300 = 1416 \text{ m}, \]
both for basic version and for other modifications under consideration.

3. Line 3-4 — by restriction of available possibility to increase the required thrust of power plant, and consequently power-weight ratio of the aircraft \( \bar{t}_{t,\text{omax}} = 1.28 \).

Increase of the required thrust of aircraft power plant in considered ratios \( 1.0 \leq \bar{t}_{t,\text{o}} \leq 1.28 \) can be provided both by availability of afterburner mode engaged automatically (in response to engine failure signal) and by possibility of installation of more high-power engines.

4. Line 4-5 — by restriction of aircraft weight from strength conditions determined by the worst cases of loading of different aircraft components (wing, tail unit, landing gear, etc.) by modes of operation. In this case it is accepted that \( \bar{G}_{t,\text{omax}} = 1.26 \).

5. Line 5-1 – by restriction \( V_0 = V_{\text{lift}} \). This restriction gives the relationship

\[ V_{b,0}^2 = V_{\text{lift},b} V_{\text{lift}} = V_{\text{lift},b} \sqrt{G_{t,0}^2}, \]

\[ \bar{G}_{t,b} = \frac{V_{b}^2}{V_{\text{lift},b}^2} V_{\text{lift}}^2 \] \( \tag{21} \)

or \( \bar{G}_{t,\text{o}} = 0.819 V_{\text{lift}}^2 \), \( \tag{22} \)

which can be considered as the complete takeoff run with one failed critical engine at liftoff (see para. 2 above).

Using the data given in Figure 2 we construct the dependence \( \bar{V}_1 = f \left( \bar{G}_{t,\text{o}}, \bar{t}_{t,\text{o}} \right) \) shown in Figure 3 on coordinates \( \bar{G}_{t,\text{o}} \) and \( \bar{V}_1 \) at different values of \( \bar{t}_{t,\text{o}} \).

4. Conclusions

Decision speed \( V_1 \) is specified in the Airplane Flight Manual and should be greater or equal to minimum maneuvering speed at takeoff run \( V_{\text{min,maneuv}} \), at which after critical engine failure aircraft control is provided by means of aerodynamic controls to maintain straight motion \( V_1 \geq V_{\text{min,maneuv}} \), and less or equal to nose landing gear lift speed which is also specified in the Airplane Flight Manual \( V_1 \leq V_{\text{NLG}} \) [19,22].

The method of quantitative estimation of influence of modifications takeoff mass and thrust-to-weight ratio variation on decision speed relative value with maintaining one of basic parameters – rejected takeoff distance, i.e. of assigned base airfields has been proposed.

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