Engineering Notes

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Airplane Economic Design Evaluation (AEDE) Computerized Model and Its Application

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Introduction

THE Aircraft Economic Design Evaluation (AEDE) system is a mathematical model designed to assist in evaluating airplane improvement programs, new designs, and in general, the impact of airplane performance on an airline's specific route system. It simulates the aircraft operation in a realistic route environment and applies economic considerations to convert all information into a single figure of merit, usually based on system cost or profitability.

An important feature is that AEDE is heavily oriented with respect to a chosen route system and will show clearly how well the aircraft under study "matches" the route system over which it is being flown. Customer service level is measured in terms of the average number of passengers out of the total demand per week that must be rescheduled (offloaded) to other flights. On a city pair basis, these average offloads are computed as a function of the given random distributions of passenger demand and takeoff airport temperature, aircraft performance description, takeoff airport description, city pair range, and aircraft seating capacity. Thus, an aircraft that is overdesigned for its route mission is clearly pinpointed by having relatively few offloads per week. Furthermore, AEDE shows the user which city pairs are limited and the severity of the limitation. Aircraft modifications beng compared over the same mission are required to provide equivalent customer service level on each city pair of the route system; i.e., total average offloads per week are adjusted to any desired target level (e.g., to that experienced by a previously flown aircraft) by making appropriate adjustments to load factor and trip frequencies. The results of separate studies on facility changes for new aircraft designs, turnaround times (utilization), and maintainability also can be fed into the AEDE model. Reference 1 contains a plea from a carrier for such analyses. A macroflow diagram of the AEDE computing system is shown in Fig. 1 and is described in this Note with examples.

Part 1 of AEDE—Basic Operating Facts

Part 1 of the AEDE program measures the basic operating facts of each aircraft separately for each of the carrier's city pair legs. The main inputs for each leg are: random distributions of passenger demand and of takeoff temperature; city pair distance and average enroute winds; trips per week; takeoff airport elevation and length; and aircraft performance description (maximum gross takeoff weight as a function of runway temperature, elevation, and length, fuel consumption vs payload, flight hours at minimum cost and long-range cruise conditions, fuel reserves and allowances, and operating empty weight).

The output of Pt. 1 of AEDE is called basic operating facts (per trip and per week for each city pair leg) and includes flight hours, block hours, fuel burned, return from fares, average capacity offloads, average performance offloads, and average number of passengers carried. Weekly route system totals for each aircraft (input to Pt. 2) are obtained by adding weekly city pair values.

For each city pair, the passenger demand per trip is input a normally distributed function with mean μ and standard deviation $\sigma = K\mu$, where K is also an input parameter. Experience with empirical modeling of various route systems has shown this method of estimating σ to be quite realistic, and that $K \simeq 0.4$.

For a fixed range, a linear relationship between fuel burned and payload and another linear relationship between reserve fuel carried and payload are used. Thus, if we let $F(Y)$ = flight fuel + air maneuver allowance (lb), Y = passenger payload weight (lb), and $S(Y)$ = reserve fuel required (lb), then $F(Y) = A + BY$, and $S(Y) = C + DY$, where A, B, C and D are input separately for each city pair range. Furthermore, A and B must be specified separately for high-speed (minimum cost) cruise conditions and long-range cruise (minimum fuel) conditions.

Finally, a slight correction is made to a given set of values of A and B to account for any given enroute winds. Let E = operating weight empty of the aircraft (lb), T = runway temperature (°F), $W^*(T)$ = maximum takeoff weight (with capability a function of T, takeoff runway length, and altitude), W = aircraft takeoff weight required corresponding to a payload demand Y for a given range, X = fuel allowance for taxi-in after touchdown (lb), Y_p = weight of a full passenger payload (lb), and $Y^*(T)$ = maximum payload capability (lb) at runway temperature T (depends on flight cruise conditions and city pair range). Then, for a given city pair flight (fixing takeoff runway length and altitude, city pair range, and

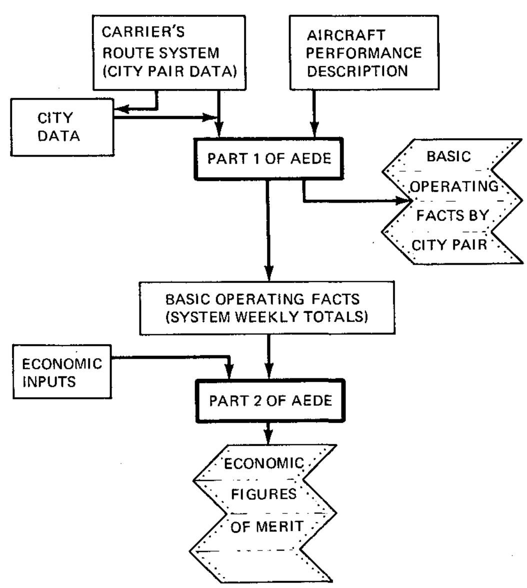

Fig. 1 Flow of data through the AEDE program.

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Table 1 Example of target-service-level factoring

	Base design	Modified design First trial	Modified design Final
Max weight, lb	775,000	744,000	
Average passenger demand	272	272	206.67
Frequency, trips/wk	7	7	9.21
Average offloads/wk			
Performance	67.87	298.31	150.47
Capacity	96.03	96.03	13.43
Total	163.90	394.24	163.90
Weighted offload value	\$45,324.71	\$109,019.03	\$45,323.82
Block hrs/trip	10.90	10.90	10.90
Block hrs/wk	76.32	76.32	100.44

cruise conditions),

$$W = Y + E + X + F(Y) + S(Y) = Y(1 + B + D) + E + X + A + C \quad (1)$$

Given T, we find $Y^*(T)$ by first computing $W^*(T)$ and using it with Eq. (1) to solve

$$Y^*(T) = (W^*(T) - E - X - A - C)/(1 + B + D) \quad (2)$$

Equation (1) is applied for each city pair to determine whether the aircraft can take off with a full passenger payload Y_p on a prescribed high percentile (e.g., 95%) hot day (T) with a prescribed high adverse wind (e.g., average plus 25 knots) flying a minimum cost cruise schedule. If it can, the city pair is classified as noncritical, and minimum cost fuel and time will be used in all subsequent calculations. If it cannot, the long-range cruise fuel and times will be used. (Any type of cruise procedure can be used in the program.)

Passenger offloads and number of aircraft required

Let $\bar{Y}(T) = \min\,[Y^*(T), Y_p]$ define the maximum payload that can be carried from the given airport over the given city pair range as a function of takeoff temperature. [Since T is a random variable, so is $\bar{Y}(T)$.] Total passenger offloads L occur whenever $Y > \bar{Y}(T)$. Total offloads include capacity offloads L_c which occur whenever $Y > Y_p$. Performance offloads are computed as their difference, $L - L_c$. Capacity offloads depend on the single random variable Y; performance offloads depend on two random variables, T and Y.

Let $F_Y(y)$ be the distribution function of Y, completely determined by the mean of Y, μ, since AEDE uses $\sigma = K\mu$ and treats Y as being normally distributed. Figure 2 illustrates how Y and T interact with each other and Y_p to produce total and capacity offloads. The formula for computed expected capacity offloads is:

$$L_c = \int_{Y_p}^{\infty} (y - Y_p)dF_Y(y) \quad (3)$$

which is independent of temperature. Again using $\bar{Y}(T) = \min\,[Y^*(T), Y_p]$, total expected offloads are computed as:

$$L(T) = \int_{\bar{Y}(T)}^{\infty} [y - \bar{Y}(T)]dF_Y(y) \quad (4)$$

Expected performance offloads are computed as:

$$L_p(T) = L(T) - L_c \quad (5)$$

Table 2 Takeoff noise vs maximum takeoff weight

Case	EPNdB	Maxweight, lb
1	108.0	775,000
2	106.5	744,000
3	102.0	658,000
4	97.5	580,000

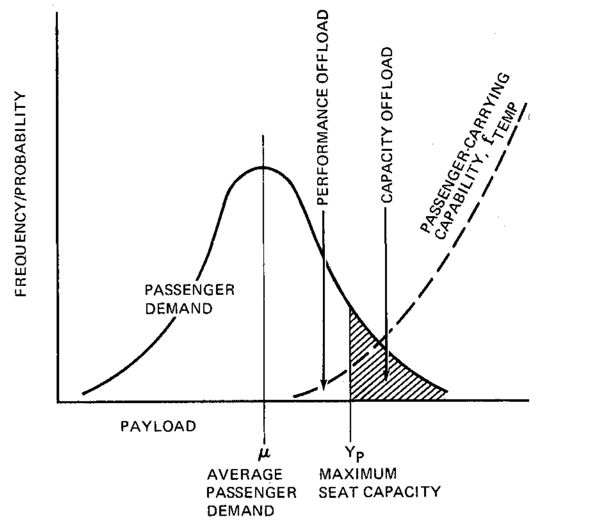

Fig. 2 Passenger demand–payload capability probability curve.

Of course if maximum gross weight $Y^*(T)$ exceeds Y_p, then $L(T) = L_c$ and $L_p(T) = 0$.

Although expected capacity offloads per trip are given unconditionally by Eq. (3), performance offloads in Eq. (5) depend on T. To obtain an unconditional expected performance offload $E(L)$, the cumulative takeoff temperature distribution is approximated at the origin sites with N discrete temperatures (T_i) and associated probabilities (P_i):

$$E(L) = \sum_{i=1}^{N} P_i L_p(T_i) \quad (6)$$

If desired, AEDE will factor the passenger demand and trip frequency to obtain a prespecified target service level for each city pair separately. Target level is in the form of weighted offload, which is usually a weighting of a number of fares per passenger offloaded. Performance and capacity offloads can be given different weights. For example, we have considered the following base-design aircraft flying from London to Los Angeles (summar quarter): 4 engines, 400-seat capacity, and 5,000-naut miles design range, with a one-way fare of \$276.54. Using as input an average demand of 272 passengers per trip and a frequency of seven trips per week, Table 1 shows that the total offloads per week were 163.9, which, at one fare per passenger offload, gives a weighted offload of \$45,324. The same aircraft was then modified by restricting its maximum gross takeoff weight to 744,000 lb (the limit for the base aircraft was set at 775,000 lb). When the modified aircraft was run over this same city pair at the same demand and frequency, the total offloads were 394.24 and weighted offloads were \$109,019. In this case, however, the base aircraft's weighted offload was given as a weighted off-

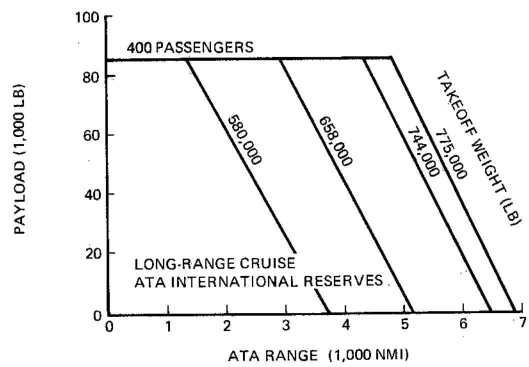

Fig. 3 Payload vs range curve.

Table 3 Basic operating facts for comparison aircraft

Case No.	Max weight lb	Number of trips	Block fuel, 10^6 lb	Block time, hr	Performance offload	Capacity offload	Total offload	Total passengers
1	775,000	850	85.91	3,923	78	3,217	3,295	158,081
2	744,000	860	87.58	4,033	308	2,987	3,295	158,081
3	658,000	1,213	153	7,572	2,202	1,093	3,295	158,081
4	580,000	2,520[a]	310	16,668	25,220	779	25,999[a]	135,377

[a] In case 4, 94 of the original scheduled trips were canceled (0 payload capability) with all passengers counted as lost.

load target to the modified aircraft. AEDE then found that by multiplying average demand by 1/1.316 and frequency by 1.316, the target weighted offload was reached. Thus, the total passenger demand per week and "service level" were made the same in both cases. The net impact is felt in the weekly block hour increase, which would require increased initial investment in aircraft as well as in operating costs.

If not specified initially, the number of aircraft required to service a given route system can be computed from average aircraft utilization (block hours per aircraft per day) and total block hours required to fly the system.

Example—impact of noise limitations

The AEDE model was used in a study of the economic impact of 1) designing an airplane to a target noise level, and 2) reducing the maximum allowable takeoff weight to operate the airplane at lower takeoff noise levels. This example represents the results of an analysis of four cases of an aircraft operating at specified takeoff noise levels. The aircraft is identical in each case except for imposed changes in maximum takeoff weight. Each case has the same route system. The basic aircraft has four engines with a bypass ratio of 5, 5000-naut miles design range, 400-seat capacity, a long-range cruise Mach number 0.84, and a 145-knot approach speed at maximum design landing weight; it requires a 12,000-ft takeoff field length at sea level and at 86°F and has a 108-EPNdB‡ target noise level. The design is representative of aircraft entering service in the early 1970's. The wing, flap, and engine technologies are close to the maximum acceptable in current designs. No major breakthrough in structural technology or materials has been assumed.

The payload range curve shown in Fig. 3 illustrates the performance of the airplane for the maximum takeoff weights shown in Table 2. Part of the route system used in the study is a set of international flights. Each of the following examples is limited to this set. Figure 4 is a histogram showing the range vs frequency. To make the route system conditions representative, summer and winter quarter conditions were treated separately and then combined on an equal basis. The average input load factor for summer was 0.55 and for winter, 0.38. All weighted offloads were computed on the basis of one fare per passenger offloaded. Case 1 weighted offloads were used as target levels for each of the other three cases.

Table 3 summarizes the results, which show that; 1) The takeoff field length limitation for the base airplane is negligible, as shown by the extremely low number of performance offloads for case 1. 2) Each increment in payload-range limitation imposed by reducing the aircraft maximum takeoff weight $W^*(T)$ accelerates the required number of trips per week. 3) Total offload (customer service level) was held the same as the base airplane, except that for case 4 the airplane became so payload-range limited that no payload could be carried between some of the longer range city pairs, which were subsequently cancelled by the AEDE model. 4) As the number of trips increased, so did the block fuel and time, modified by the following considerations: a) as the aircraft became more limited, more of the flights were flown at long-range cruise speeds (less fuel, more block hours) than were originally flown at the higher speed minimum-cost type cruise, and b) the increased number of flights were at longer ranges, i.e., they consumed more fuel and time than the average flight.

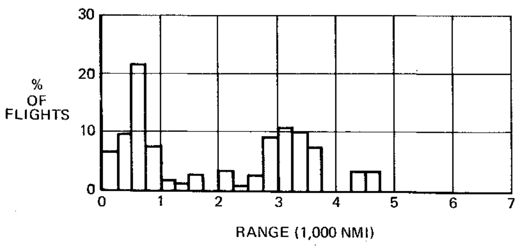

Fig. 4 Route system histogram.

‡ EPNdB means effective perceived noise, measured in decibels.

Part 2 of AEDE—Economic Evaluation

Each aircraft over its route system is simulated separately by Pt. 1 of AEDE; Pt. 2 conducts simultaneous economic comparisons of a pair of these simulations (same route system, different aircraft) and displays intermediate results side by side. Inputs to Pt. 2 are the route system weekly totals of the basic operating facts generated by Pt. 1 and economic inputs as follows: aircraft selling price, spares; separate DOC cost rates—\$/flight hour (maintenance material and labor), \$/block hour (crew pay and oil), \$/cycle (maintenance material and labor), fuel cost, and insurance rate; and aircraft indirect operating cost over the given route (\$/trip). Miscellaneous inputs are aircraft life (yr) and rate of interest of money (%/yr).

An illustration of a few sample economic figures of merit used here is given in the following paragraphs. Let us consider a change of $W^*(T)$ using cases 1 and 2 of the example given in Table 3; i.e., $W^*(T)$ is reduced from 775,000 to 744,000. The results are displayed in Table 4.

In the first case 158,081 passengers per week were carried (3295 were offloaded) in 850 trips, requiring a total of 3923 block hours. To match this service level in the second case,

Table 4 Impact with changes on maximum gross weight for 4-engine, 400-seat aircraft of 5000-naut miles design range; route system average range, 1969 miles; aircraft price, \$25.238 million

	Case 1	Case 2
Max weight	775,000	744,000
Average passengers carried per week, PC	158,081	158,081
Average passenger offload per week	3,295	3,295
Trips per week, t	850	860
Block hrs per week	3,923	4,033
Load factor, $P/400t$	0.4649	0.4595
Average utilization	11.70	11.71
Number of aircraft required	47.92	49.19
Total aircraft price, 10^6 \$	1,209	1,241
Weekly return from fares, 10^6 \$	22.697	22.697
Weekly operating costs, 10^6 \$	12.170	12.305
Weekly gross profit, 10^6 \$	10.527	10.392
Net profit per dollar invested present value, \$	2.1617	2.0405

the total weekly trip frequency had to be increased to 860, requiring a total of 4033 block hours. The average load factor decreased from 0.4649 to 0.4595. The increase in block hours caused the total aircraft investment price to increase by $32,000,000.

Customarily, depreciation is included as part of operating cost. This has not been done here. AEDE treats investment cost more realistically by converting net weekly profit to present value of gross weekly profit over y years and $i\%$ interest on money. The result is compared with total present dollars invested in aircraft.

The net impact of lowering $W^*(T)$ can be visualized by comparing figures of merit; e.g., the present value of profit per dollar invested in aircraft decreases from $2.16 to $2.04 (Table 4). Other figures of merit are available to the AEDE user, e.g., net profit present value, present value of gross profit, or total annual cost.

In conclusion, AEDE provides a fair economic comparison between competing aircraft over the same route system. Its use can be extended to provide sensitivities to changes to aircraft performance, aircraft sizing, route system modification, changes in economic variables, and turnaround times and through stop capability.

Reference

[1] Lloyd-Jones, D. J., "Airline Equipment Planning, AAIA Paper 67-392, Los Angeles, Calif., 1967.

Dynamic Stall Simulation Problems

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DYNAMIC airfoil stall is a problem of concern both to compressor and helicopter industry. The problem has so far defied theoretical solution, and the only recourse has been simulation of dynamic stall in ground facilities, such as wind tunnels. Already static airfoil stall is difficult to simulate due to wind-tunnel wall and support interference, and the sensitivity of stall to surface roughness, Reynolds number, and wind-tunnel turbulence. This is at least true for trailing-edge and leading-edge stall, the two stall types of practical interest for the relatively thick airfoils used for compressor and helicopter blades. In the dynamic case, there are additional simulation problems associated with the effects of the airfoil oscillation on the effective adversity of the pressure gradient and the effective air turbulence (or Reynolds number).

It can be shown that the measured undamping at stall is caused by the pitch-rate induced accelerated flow effect and resultant delay of separation and reattachment.[1] The accelerating flow on the leeward side of a pitching airfoil causes a decrease in the adversity of the pressure gradient, resulting in a large overshoot of the static stall.[2] A similar lessening of the adversity of the pressure gradient can be accomplished by "nose droop," also resulting in an overshoot of the stall.[3]

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Index Category: Nonsteady Aerodynamics; Airplane and Component Aerodynamics.

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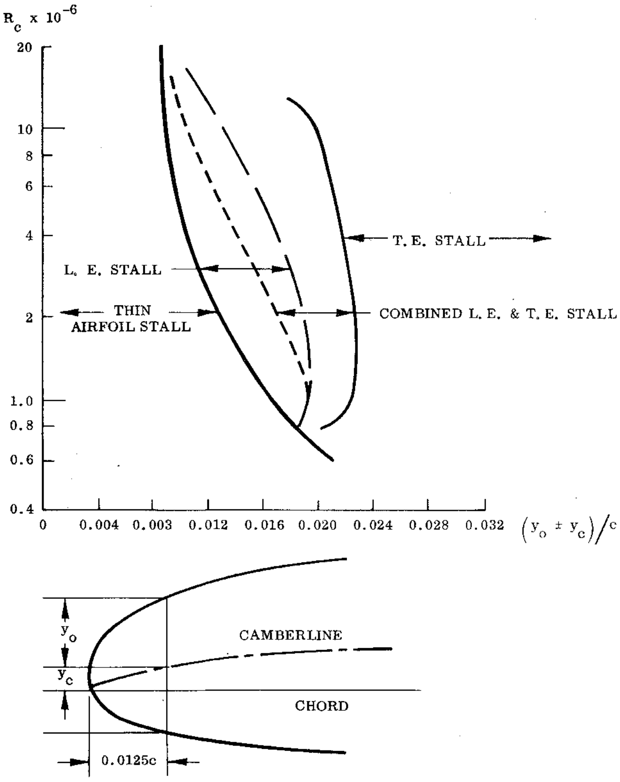

Fig. 1 Reynolds number airfoil thickness map for transition between stall types (Ref. 4).

That is, the pitch rate induces a change of the effective airfoil shape.

Gault[4] has shown that the stall type is determined by the Reynolds number and a profile coordinate that effectively is a measure of the leading-edge curvature (Fig. 1). The figure is very instructive and demonstrates that it will take very little change in camber to convert leading-edge stall to trailing-edge

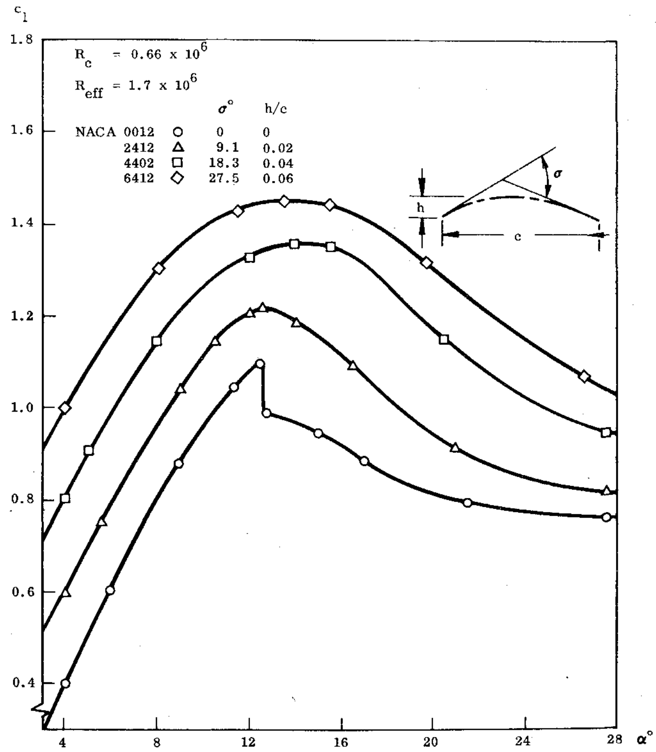

Fig. 2 Effect of camber on stall pattern of NACA-0012 airfoil section (Ref. 5).