

Design Drivers of Energy-Efficient Transport Aircraft

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ABSTRACT

The fuel energy consumption of subsonic air transportation is examined. The focus is on identification and quantification of fundamental engineering design tradeoffs which drive the design of subsonic tube and wing transport aircraft. The sensitivities of energy efficiency to recent and forecast technology developments are also examined.

BACKGROUND AND MOTIVATION

Early development of the modern jet transport, starting with the DeHavilland Comet and Boeing 707 in the 1950's, was strongly driven by range requirements. With the imperatives of rising fuel costs and increased environmental concerns, more recent developments have focused on fuel economy and also on noise. Of the three main drivers of fuel economy - aerodynamics, structures, and propulsion - the latter has seen the largest improvements, not surprisingly because in the 1950's turbojet and turbofan engines were a very young technology. As engine technology maturation has now reached the levels of the other disciplines, further improvements will have to come from all technologies. The recent and ongoing NASA Aeronautics research,¹ in particular the N+1,2,3 programs² target a wide range of aerodynamic, structural, and propulsion technologies towards this goal.

The objective of this document is to identify the major competing effects: which influence the design parameters of a tube and wing transport aircraft, optimized for minimum fuel burn. Sensitivities of fuel burn to the following parameters will be determined and presented:

- flight Mach number
- allowable specific stress and load factor
- allowable turbine metal temperatures
- engine overall pressure ratio
- balanced field length
- stability margin

Recent configuration technologies from the N+3 program will also be mentioned.

The main focus will be on short to medium-range Boeing 737 or Airbus A320 class aircraft, since this is one of the largest air travel market segments. Longer range aircraft in the Boeing 777 or Airbus A340 class will also be examined for a few cases.

The overall objective is to identify which parameters or combinations of parameters have the greatest potential for enabling fuel burn reductions, and therefore are the most attractive targets for research and development.

FUEL CONSUMPTION OVERVIEW

We will begin by examining the major overall factors which contribute to fuel burn, via the Breguet relation. This analysis is too coarse to provide any useful design guidance, but it does help to interpret some possibly counterintuitive results from much more detailed optimization results presented later.

FUEL CONSUMPTION VIA BREGUET RELATION

The fuel weight W_{fuel} consumed to fly a distance (range) R by an aircraft in level flight at Mach number M is given by the Breguet relation.

$$W_{\text{fuel}} = W_{\text{ZF}} \left[\exp \left(\frac{D}{L} \frac{TSFC}{M} \frac{R}{a} \right) - 1 \right] \quad (1)$$

$$\simeq W_{\text{ZF}} \times \frac{D}{L} \times \frac{TSFC}{M} \times \frac{R}{a} \quad (2)$$

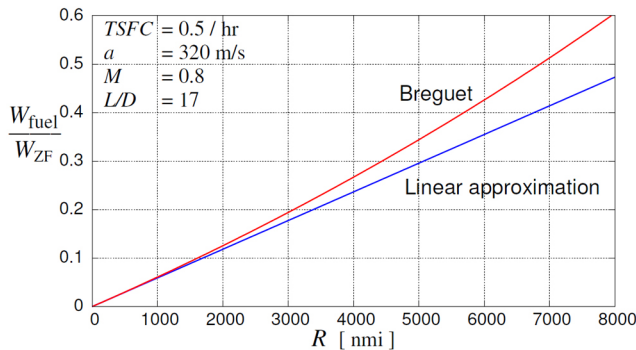


Fig. 1. Fuel weight fraction versus mission range for a typical jet transport. The linear approximation is valid for short to medium range missions.

The exact and linearized forms (1), (2) are compared in Figure 1 for a typical modern jet transport. Long range missions in effect get progressively more penalized for carrying the extra fuel. The linearized form shows that the fuel weight is approximately the product of three parameters:

W_{ZF} Zero-fuel weight (at landing).

D/L Drag/lift ratio.

$TSFC/M$ Thrust-specific fuel consumption over Mach

The range R is fixed by the mission and the speed of sound a at cruise altitude is a physical constant, and hence these are not design variables. In the limit of very high-bypass ratio engines or lightly-loaded propellers, the $TSFC$ scales nearly as the cruise Mach M . In this situation the ratio $TSFC/M$,

which is equivalent to a power-specific fuel consumption, is the relevant measure of propulsion-system efficiency. For a fixed-parameter turbofan engine, the ratio $TSFC / M^{0.5}$ stays roughly constant with M , while for an optimized engine the ratio $TSFC/M^{0.7}$ is roughly constant. The corresponding aerodynamic figures of merit for the two approaches are then $M^{0.5}L/D$ and $M^{0.3}L/D$, respectively. Which approach is chosen is largely a matter of preference when performing manual parametric studies. The choice is immaterial for the parameter studies presented here, since the engine is simulated directly, for any given M , without reliance on any assumed empirical $TSFC$ vs. M dependency.

Although equations (1) and (2) correctly give the fuel burn, they are nearly useless as a design guide. The reason is that any one of the three parameters can be reduced in isolation, but this will generally increase the others. For example, D/L can be reduced by increasing the wing aspect ratio or the wing/wetted area fraction, but this will be offset by an increase in the wing weight's contribution to W_{ZF} . The $1/M$ factor can be decreased by choosing to fly faster, but this will increase all the other factors and actually give a net increase in the fuel burn. Since all the factors influence each other to varying degrees, to minimize fuel burn it is essential to account for their important interactions and tradeoffs. This is addressed by the conceptual-design approach, whose application is the central focus of this paper.

FUEL BURN AND FLIGHT ALTITUDE

From the most fundamental viewpoint, the objective of air transportation is to move the fuselage - in effect a payload container - over a required range R , at an economically-viable speed or Mach number, with the smallest fuel weight or more generally energy expenditure. The latter is quantified by the Payload- Fuel Energy Intensity (PFEI),³

$$\begin{aligned} PFEI &\equiv \frac{h_{\text{fuel}} W_{\text{fuel}}}{W_{\text{pay}} R} \quad [\text{kJ/kg km}] \\ &= \frac{\text{Fuel energy}}{\text{Payload mass} \times \text{Distance}} \end{aligned} \quad (3)$$

where h_{fuel} is the fuel specific heating value. This allows an energy-usage efficiency comparison between different aircraft and mission lengths, between different fuels, and between different modes of transportation (air, land, water).

To examine a transport aircraft's energy requirements in this framework, expression (2) is recast by separating the components of the drag D , assuming $W_{\text{ZF}} \simeq L$, and defining an effective power specific fuel consumption based on thrust power $PSFC_T \equiv TSFC/V$.

$$PFEI \simeq (D_{\text{fuse}} + D_{\text{rest}} + D_i) PSFC_T \frac{h_{\text{fuel}}}{W_{\text{pay}}} \quad (4)$$

The absolute minimum energy required to transport the fuselage is

$$PFEI_{\text{min}} = D_{\text{fuse}} PSFC_T \frac{h_{\text{fuel}}}{W_{\text{pay}}} \quad (5)$$

with the energy consumed by the induced drag and the profile drag of the remaining components being in effect “overhead”. D_{fuse} and the corresponding $PFEI_{\text{min}}$ can be quantified via the usual average skin friction, form factor, and wetted area, as described by Shevell.⁴

$$PFEI_{\text{min}} = \frac{\gamma}{2} p M^2 C_{f_{\text{wet}}} F_f A_{\text{wet}} PSFC_T \frac{h_{\text{fuel}}}{W_{\text{pay}}} \quad (6)$$

The dynamic pressure has also been replaced by the static pressure p and flight Mach number by the relation $\rho V^2 = \gamma p M^2$.

The effect of Mach number will be examined in detail later. If this is considered fixed, then aside from reduced $C_{f_{\text{wet}}}$ via riblets or laminar flow (which will also be examined later), the only variable in (6) which can be freely varied to significantly reduce $PFEI_{\text{min}}$ is the pressure p at cruise altitude. Indeed, transportation of the fuselage is “free” if performed at extreme altitudes where $p \simeq 0$. But of course an increase in flight altitude adds more “overhead” in the form of larger and heavier surfaces and engines, whose profile and induced drag add to the full fuel energy expression (4). This tradeoff is quantified in Figure 2. The optimum altitude for any given Mach number is where the fuel burn due to fuselage drag and due to overhead have equal and opposite sensitivity to pressure.

It's interesting (if not amusing) to consider transporting the fuselage at sea level as a wheeled vehicle, since this eliminates the weight and drag overhead of the wings and tails, and also eliminates induced drag. As indicated in Figure 2, the energy required to do this is actually comparable to the energy needed to fly the fuselage at the optimum altitude at the same Mach number. Needless to say, a wheeled fuselage traveling overland at $M=0.8$ is not practical.

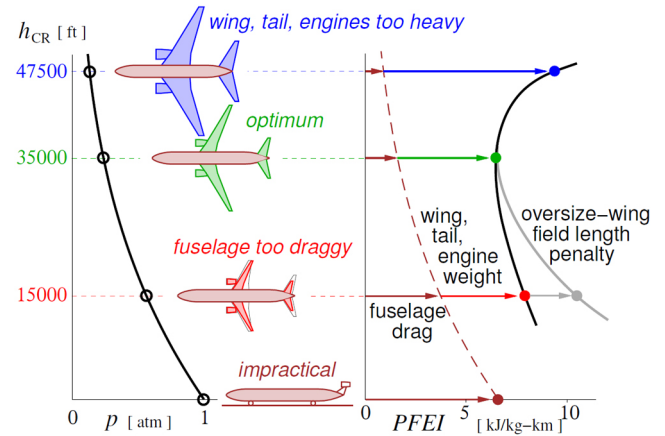


Fig. 2. Mission fuel-energy use versus cruise altitude for a jet transport with a B737-class fuselage, at fixed cruise Mach $M_{CR} = 0.8$. Lower pressure at altitude decreases fuel burn from fuselage drag, but increases fuel burn from “overhead” of wings, tails, engines.

TRANSPORT AIRCRAFT DESIGN SPACE

CONCEPTUAL DESIGN FORMULATIONS

At the detail-design level, a vast number of parameters is needed to fully define an aircraft, its engines, and its operation. A major goal of the initial conceptual design stage is to greatly reduce the number of parameters by some combination of historical correlations and low-order modeling, and thus allow initial sizing and optimization.

Because aircraft fuel burn depends on many competing drivers, any effective conceptual design formulation must retain the key features of all the disciplines involved. As a minimum, the airframe structure and weights, the aerodynamic performance, the propulsion performance, and the flight trajectory must all be represented with sufficient fidelity. Many conceptual design approaches have been developed towards this end, e.g. by Roskam,⁶ Torrenbeek,⁷ Raymer,⁸ Jayaram,⁹ Mason,¹⁰ and others.

Conceptual design methods more focused on formal optimization have also been developed. These are commonly referred to as Multi-Disciplinary Optimization, or MDO methods. Examples are the methods of Knapp,¹¹ Wakayama,¹² and Kroo.¹³ The author's TASOPT formulation¹⁴ also falls into this class.

TASOPT SUMMARY

Because TASOPT was used to generate the key results in this paper, a brief summary is given here so the fidelity as well as limitations of the results can be better understood. TASOPT uses first-principles methods for its primary weight, aerodynamic, and engine performance predictions. Specifically, it uses

- Beam and pressure-vessel theory for primary-structure sizing and weight prediction, [Figure 3](#).
- Variable wing airfoils and viscous/inviscid CFD for all profile drag prediction, [Figure 4](#).
- Full engine flowpath simulation, [Figure 5](#).
- Variable flight trajectory, [Figure 6](#).

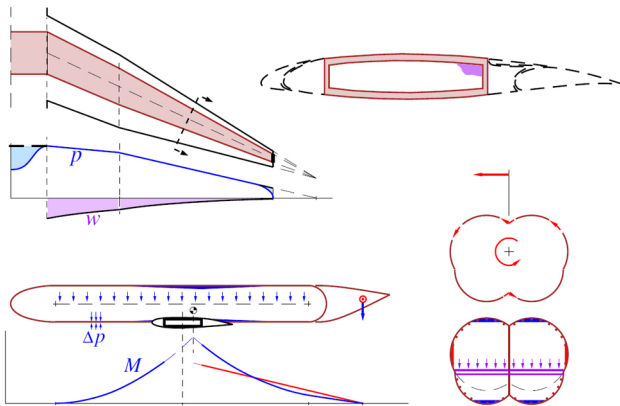


Fig. 3. TASOPT structural and weight models for wing and fuselage, based on simple beam and pressure-vessel theory.

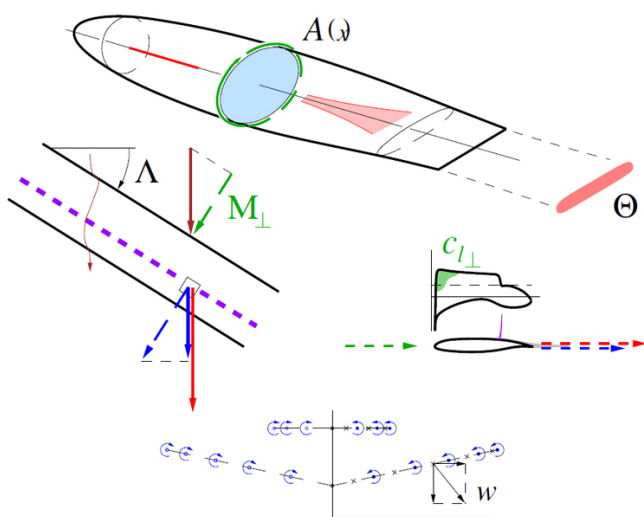


Fig. 4. TASOPT wing and fuselage profile drag models, and Trefftz-Plane induced drag model.

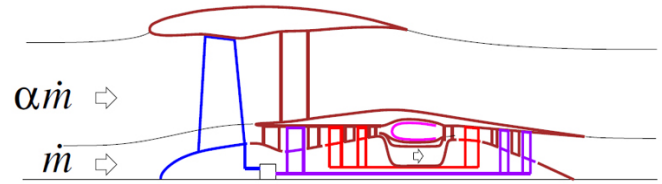


Fig. 5. TASOPT turbofan engine performance model. The entire flowpath is simulated, including the effects of turbine cooling flow.

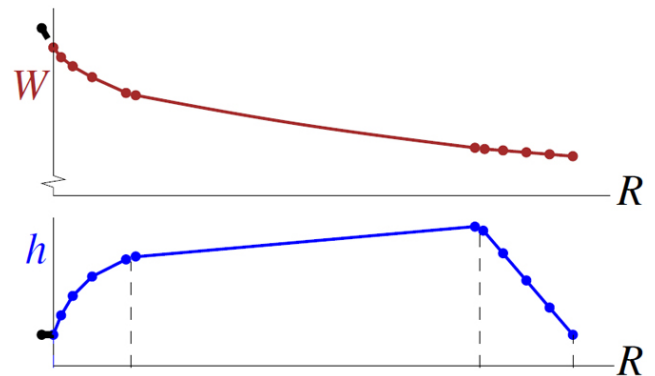


Fig. 6. TASOPT trajectory simulation for takeoff performance and mission fuel burn.

Significantly, TASOPT does not rely on historical primary-structure weight correlations, wetted-area drag prediction methods, engine lookup tables or correlations, or fixed climb and cruise profiles. The minimal reliance on historical data and empiricism gives considerable confidence in the design parameter sweeps presented here, even if they go into uncharted territory. For more detailed TASOPT documentation and validation see Drela¹⁴ and Greitzer.¹⁵

DESIGN CLOSURE AND OPTIMIZATION

For any given set of *model parameters*, design closure is the convergence of all the derived model quantities towards a self-consistent design. Such a “closed” design meets all structural criteria, and also mission requirements such as range, takeoff distance, and climb gradient. Optimization can then be performed around this closure procedure. In TASOPT this is implemented as two nested loops, shown in [Figure 7](#).

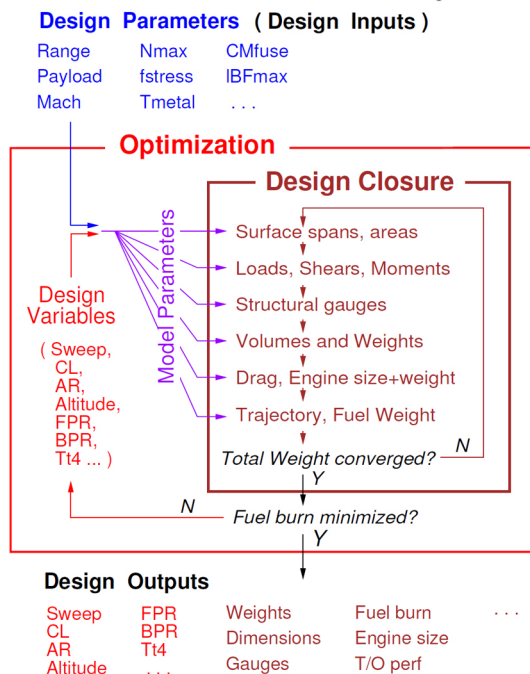


Fig. 7. TASOPT design-closure and optimization procedure. The Model Parameters required by the inner closure loop are partitioned into the Design Parameters which are explicitly specified, and Design Variables which are calculated by the outer optimization loop.

DESIGN VARIABLE SUBSET

Of the 100 or so model parameters required to define the aircraft at the conceptual level, a much smaller subset is eligible for use as *design variables* in the outer loop. These are the model parameters which have a non-monotonic influence on the fuel-burn design objective, and hence must be determined via optimization if the optimum aircraft is to be obtained. The remaining model parameters are the *design parameters*, and are typically set to the best-available values limited by technology, with some allowance for cost.

Table 1 gives the complete list of the design variables used in the TASOPT formulation. The $()_i$ index goes over some number of spanwise stations, so that λ_i define the planform shape, and $\lambda_i r_{c_{\ell_i}}$ define the spanwise-loading shape.

IMPORTANCE OF GLOBAL OPTIMIZATION

A major focus of this paper is the quantification of fuel burn versus a number of key design parameters related to technology. An essential feature of this study is that for any set of input design parameters (at the top of Figure 7), the fuel burn of the optimized aircraft is taken as the figure of merit.

Table 1. Design variables determined by global mission optimization

$C_{L_{CR}}$	cruise lift coefficient
AR	aspect ratio
Λ	wing sweep angle
λ_i	section relative chords (taper ratios)
$(t/c)_i$	section airfoil thicknesses
$r_{c_{\ell_i}}$	section local/root c_{ℓ} ratios
FPR_D	design fan pressure ratio
BPR_D	design bypass ratio
$T_{t4_{TO}}$	turbine inlet temperature at takeoff
$T_{t4_{CR}}$	turbine inlet temperature in cruise
h_{CR}	start-of cruise altitude

The importance of this continuous optimization is illustrated in Figure 8. If the cruise Mach number of the

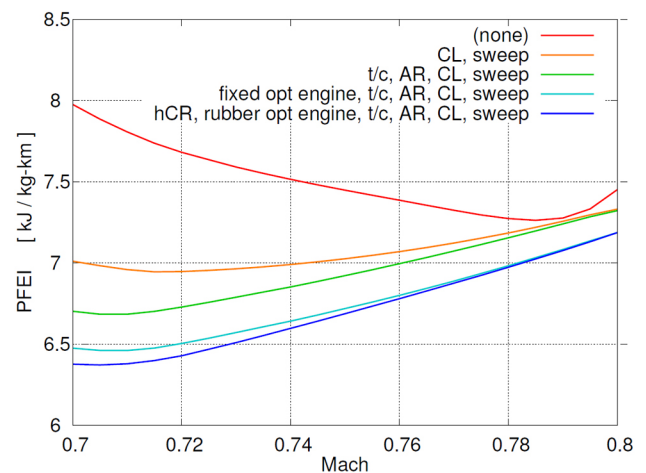


Fig. 8. Fuel burn versus cruise Mach, for different optimization design variable sets. Expanding the design set reduces the minimum fuel burn, and also changes the optimum cruise Mach.

baseline B737 is reduced, and all the other model parameters are held fixed, the result is an increase in the fuel burn as indicated by the topmost line in Figure 8. As more and more model parameters are included in the optimized design variable set, however, then progressively larger fuel savings are obtained with the slower cruise. The greatest fuel reduction occurs if all the variables listed in Table 1 are optimized. Clearly, optimizing the entire aircraft+engine+operation system is necessary to obtain the true design-parameter sensitivity, with respect to Mach number in this case. Such full optimization will be used for the subsequent sensitivity studies, so that the results represent the greatest possible fuel savings from a change in each design parameter being considered.

DESIGN PARAMETER SENSITIVITIES

The subsequent sections show the optimum-aircraft fuel burn sensitivity with respect to key design parameters. These are chosen based both on their influence on fuel burn in potential future aircraft, and on their strong dependence on technology. The results can be interpreted as a guide to research investment for future aircraft, in that they quantify the potential fuel-economy payoff of the parameters being examined.

Two baseline aircraft will be examined: a medium range aircraft in the Boeing 737 or Airbus A320 class, and a long range aircraft in the Boeing 777 or Airbus A340 class. Their specified key parameters are listed in [Table 2](#), and will be held fixed except where stated otherwise. The payloads correspond to 180 and 500 all-economy passengers, respectively. Since the range and payload are fixed, W_{fuel} and $PFEI$ are effectively equivalent. The fuel burn will also be given as a ratio from the baseline, to more easily see the potential fuel savings as a percentage.

Table 2. Key parameters of baseline aircraft.

	B737-class	B777-class
Fuse.OML	737-800	777-300ER
Payload	37 000 lb	115 000 lb
Range	3000 nmi	6500 nmi
Mach	0.80	0.84
Field	8000 ft	9500 ft

Although the fuselage outer mold lines are held fixed, the wing and tail surfaces are always sized and wing is positioned based on required-lift, trim, and stability requirements. All structural gauges are likewise always sized via specified load conditions and material properties. Conventional aluminum materials are assumed. Engines are sized for the cruise-thrust condition, under the constraint of a minimum specified balanced field length and minimum climb gradient.

CRUISE MACH NUMBER

A reduced cruise Mach number has previously been considered as a means for reducing mission fuel burn.² One drawback of the reduced speed is a negative impact on airline productivity and passenger acceptance, especially for long-range missions. For short- to medium-range aircraft, however, the flight-time increase is less problematic thus making slower cruise an attractive possibility.

[Figure 9](#) shows the relative fuel burn and other parameters of interest for a B737-class aircraft for a range of specified cruise Mach numbers. The plots show a “rubber system” spectrum, with each point on the horizontal axis representing a different airplane, engine, and flight profile combination, all optimized together for that Mach number. Optimization was performed with and without a span constraint, since a span increase has implications on compatibility with existing airport infrastructure.

The three sketches at the top of [Figure 9](#) show three airplane geometry instantiations for the three $M_{\text{CR}} = 0.7, 0.75, 0.8$ values. The optimization procedure chose the wing sweep angle shown, along with all the other design variables listed in [Table 1](#). Also, the inside design-closure loop shown in [Figure 7](#) generated all the key airframe gauges and engine parameters in the optimization process.

As the cruise Mach number M_{∞} is reduced the optimum sweep angle Λ is also reduced, roughly according to the infinite swept wing relation

$$\cos \Lambda \simeq \frac{M_{\text{crit}}}{M_{\infty}} \quad (7)$$

where M_{crit} is in the range 0.70 ... 0.75 for modern transonic airfoils, depending on the airfoil thickness t/c and the local lift coefficient. Relation (7) indicates that as $M_{\infty} \rightarrow M_{\text{crit}}$, then $\cos \Lambda \rightarrow 1$ and the sweep angle tends to approach zero. As the sweep is reduced, the optimum aspect ratio AR will then tend to increase as allowed by the reduction of structural span for a given aerodynamic projected span.

The engine parameters also change significantly, with the cruise-condition bypass ratio BPR_{CR} increasing notably as M_{CR} decreases. A major reason is that the fan face always requires a fixed local $M_{\text{fan}} \simeq 0.6$, so a lower cruise Mach results in a smaller required diffusion $M_{\text{CR}} - M_{\text{fan}}$. The less-loaded nacelle then has smaller superelevations on its outside surface, as shown in [Figure 10](#). This mitigates the nacelle profile drag penalty of a large-diameter fan, and thus the system optimizes to a larger bypass ratio.