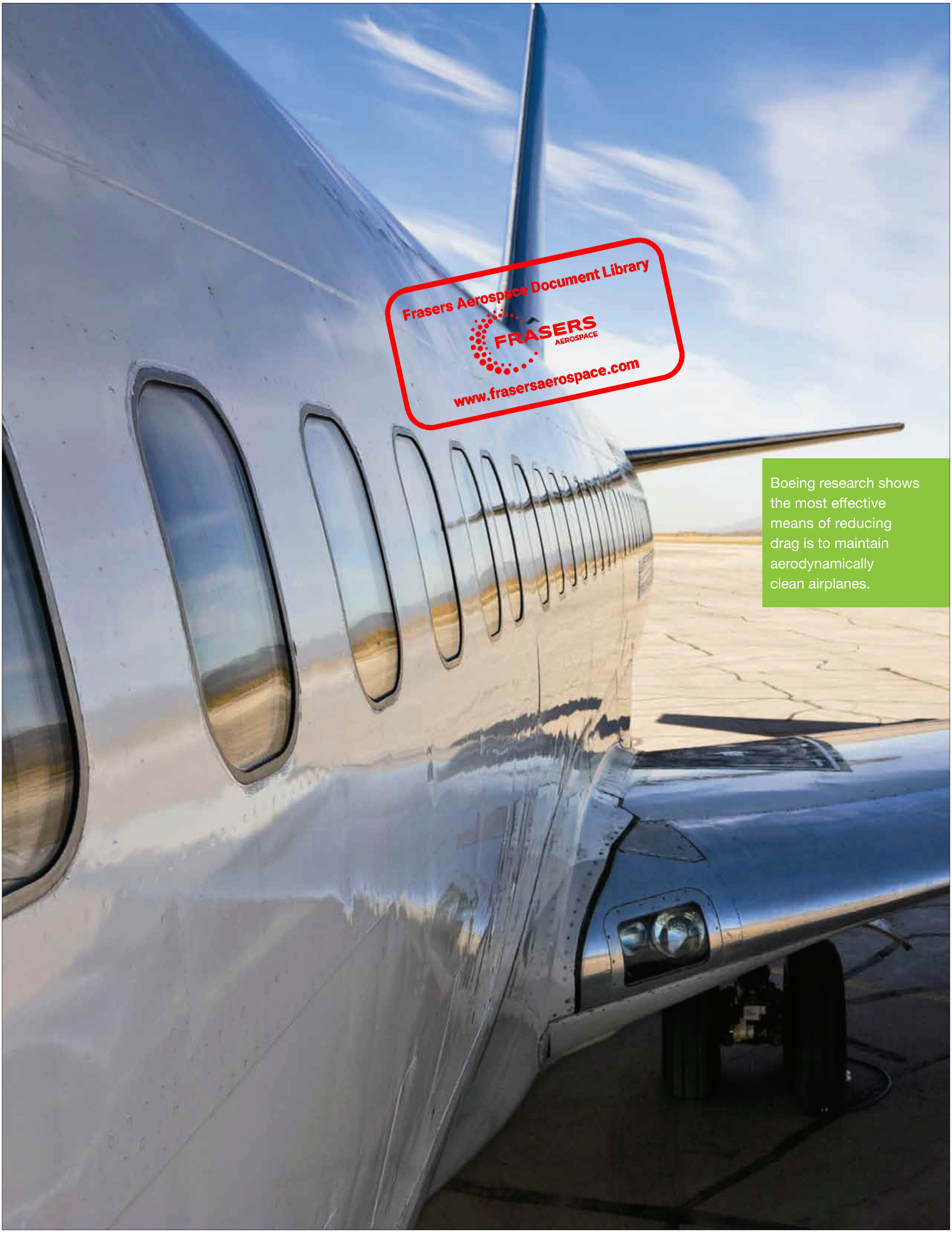

Boeing research shows the most effective means of reducing drag is to maintain aerodynamically clean airplanes.

Surface Coatings and Drag Reduction

Fuel cost is easily the largest contributor to cash airplane-related operating costs (CAROC), ranging from 40 percent to 50 percent for single-aisle airplanes and from 50 percent to 60 percent for larger twin-aisle airplanes, at recent fuel prices. Airline customers are keenly aware of the aerosmoothness of their airplanes due to its direct impact on fuel burn. With increasing fuel costs, airlines are looking for new ways of reducing aerodynamic drag of their airplanes to lower fuel consumption.

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Boeing invests significant resources to improve the performance of its commercial airplanes, including improvements for aerodynamic drag, weight, and engine efficiency. Most of the drag characteristics of the airplane are set during the initial design. Key characteristics that affect drag are wing span, exposed surface area, aerodynamic shapes, and numerous design details. After initial design, aerodynamic drag can still be improved. For example, span can be increased or winglets can be added to reduce induced drag, or drag due to lift. Aerosmoothness, or excrescence drag, can also be reduced through detailed design of the fit and fair of external surfaces, through better seals around movable surfaces such as landing gear doors and control surfaces, and through cleanup of other external protuberances.

Recently, a number of Boeing customers have become aware of claims that external surface finish coatings can provide skin protection, paint life improvement, and also skin friction drag reduction. This article provides operators with the technical background to help them assess the potential of surface coatings to reduce roughness drag. It also summarizes other techniques that Boeing recommends to reduce drag and fuel consumption.

POSSIBLE AIRFLOW PHYSICS RATIONALE FOR ROUGHNESS DRAG REDUCTION

In response to numerous questions raised by Boeing customers regarding the efficacy of surface coatings to reduce drag, Boeing has

Figure 1: Laminar versus turbulent boundary layers

Boundary layer growth (top) and velocity profile (bottom).

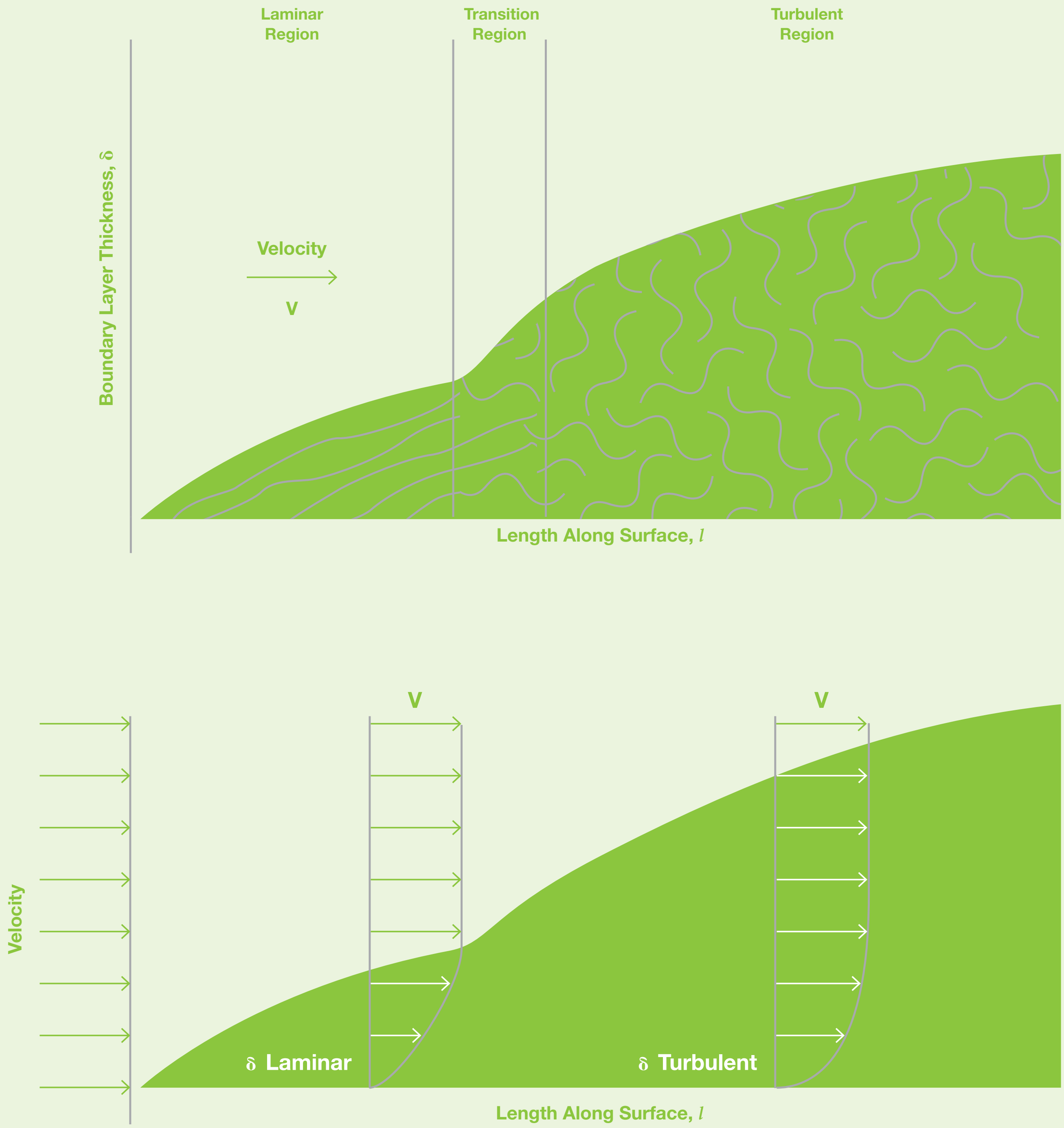
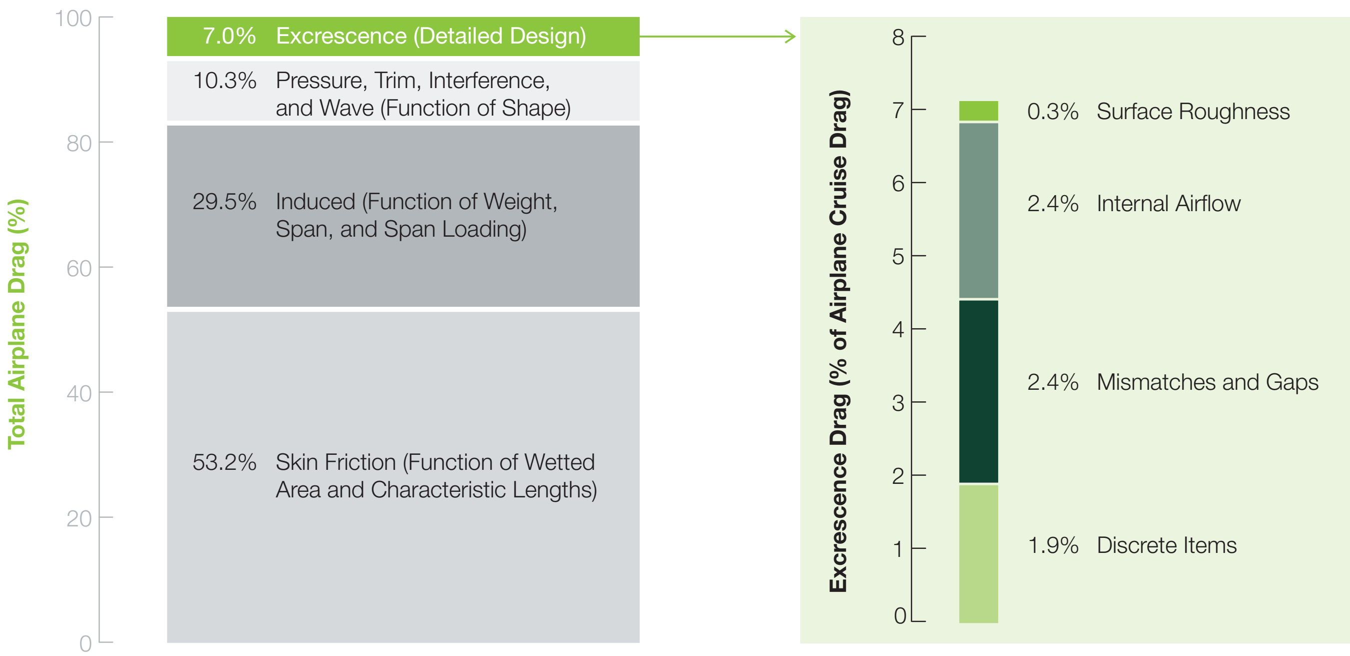


Figure 2: Typical drag component breakdown for Boeing 737

Surface roughness accounts for approximately 0.3 percent of total airplane drag.



investigated some possible airflow physics explanations. Possible explanations postulated by Boeing aerodynamicists include:

- Increased regions of laminar flow due to reduced surface roughness.
- Reduction in surface roughness resulting in lower skin friction drag, when flow is turbulent.
- Reduction in dirt and/or insect adhesion resulting in reduced roughness and hence reduced skin friction drag.

Boeing has thoroughly researched these possible explanations to determine whether methods such as surface coatings can produce a meaningful reduction in drag.

LAMINAR FLOW

The first postulated flow mechanism that may result in reduced skin friction drag due to surface coatings is the promotion of laminar flow. Laminar flow refers to the state of the boundary layer, the thin layer of air next to the airplane skin where the effects of friction would be observed. Normally, the boundary layers on large commercial airplanes are nearly all turbulent, meaning the airflow within the boundary layer is characterized by irregular flow eddies. Laminar boundary layers are characterized by more orderly flow and have significantly less skin friction drag (see fig. 1).

Current Boeing commercial airplanes are not expected to have significant regions of laminar flow, with the exception of the 787 nacelles near the inlet lip, as expressly designed. There may be very limited regions of laminar flow near the leading edges of wings, especially lesser swept wings such as used on the 737 and 757, and blended winglets.

Surface irregularities can cause the boundary layer to transition from laminar to turbulent flow in a shorter distance along the surface than may be achievable with a smoother surface finish. Surface coatings may reduce the local irregularities and extend the distance to the laminar-turbulent transition, hence reducing drag. However, the total surface area that could benefit from such improvements is extremely small, and simple calculations have shown that a small increase in the extent of laminar flow would not result in a measurable drag reduction.

Boeing has concluded that the finished skins on Boeing commercial airplanes, both aluminum and composite, are essentially hydraulically smooth. The equivalent sand grain roughness of the skins of Boeing airplanes is typically less than 400 microinches. As a result, very little additional roughness drag can be assessed beyond normal skin friction dominated by turbulence in the boundary layer.

SURFACE ROUGHNESS

Surface roughness is one of many components that contribute to drag (see fig. 2). Boeing studies and test data indicate that surface roughness typically accounts for less than 1 percent of total airplane cruise drag. These studies included design requirements for surface roughness, the effect of various surface finishes on surface roughness, and wind tunnel testing of specific surface specimen.

As a result of these studies, Boeing has concluded that the finished skins on Boeing commercial airplanes, both aluminum and composite, are essentially hydraulically smooth. The equivalent sand grain roughness of the skins of Boeing airplanes is typically less than 400 microinches. As a result, very little additional roughness drag can be assessed beyond normal skin friction dominated by turbulence in the boundary layer (see fig. 3). These studies concluded that additional coatings would not materially reduce the turbulent flow skin friction drag.

REDUCTION IN DIRT ADHESION

Surface coatings have been observed to reduce washing frequency requirements for commercial airplanes, with a typical improvement from a 60-day to a 240-day cycle. The resulting reduction in dirt and insect adhesion could result in reduced excrescence drag. Boeing believes that reduced dirt adhesion is the only postulated flow mechanism that has observable supporting evidence.

DRAG BENEFIT OF WASHING AIRPLANES

Fluids (i.e., hydraulics, oil, fuel) leaking onto the exterior surfaces of an airplane are the main causes of surface contamination by dirt and dust. This sticky layer of contaminants provides the basis for a buildup of contamination by dirt, dust, and other airborne particles. Insect remains are also common sources of contamination, especially near wing and empennage leading edges and nacelle inlets.

Engine struts, the lower aft fuselage, and the lower surface of the wing (particularly the lower surfaces of the flaps and flap track fairings) experience the highest level of contamination, making the surface rough and potentially increasing excrescence drag.

Figure 3: Definition of hydraulically smooth

A surface that is hydraulically smooth exhibits no effects of decreasing skin friction as roughness decreases. The amount of roughness on a typical airplane is below the generally accepted boundary for a hydraulically smooth surface.

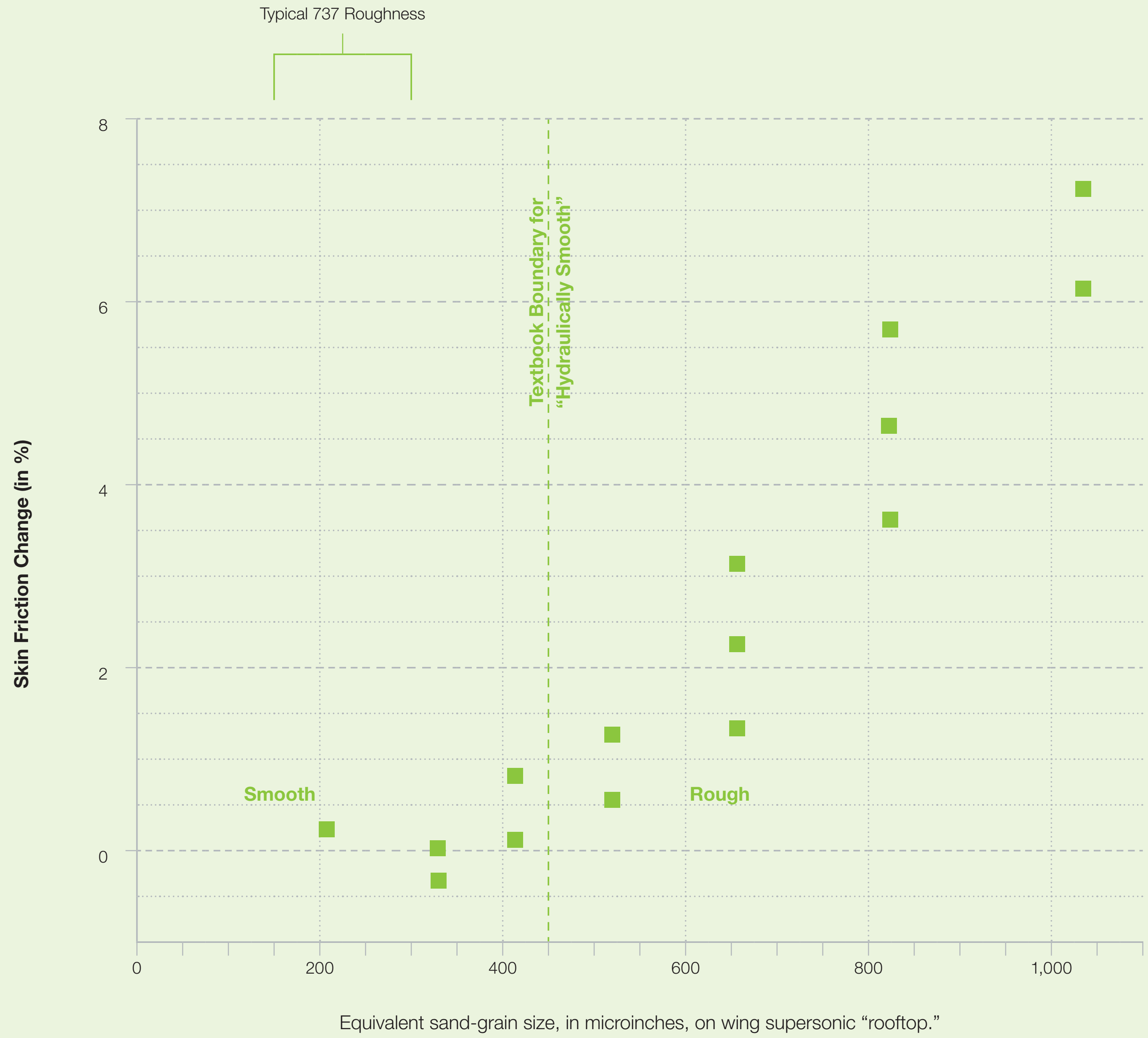


Figure 4: Estimated fuel burn penalty of unwashed airplanes

The expected fuel burn penalties associated with an unwashed airplane are based on the listed reference mission stage length and number of flights per year, factoring the results for alternate usages. The penalties also assume the same ratio of contaminated area to the airplane's respective reference wing area exists, as was observed in an inspection of an in-service 747 airframe (12 percent). If an airplane has a greater level of surface roughness, and/or a higher percentage of surface area being contaminated, the actual fuel penalty may be higher than shown here.

Airplane Model	Fuel Burn Penalty (U.S. Gal/Year/Airplane)	Reference Mission/Utilization
Next-Generation 737	2,200	500 nmi mission 2,420 flights/year
767	7,000	3,000 nmi mission 725 flights/year
787-8	10,300	6,000 nmi mission 470 flights/year
777	15,500	6,000 nmi mission 470 flights/year
747-400/-8	21,700	6,000 nmi mission 470 flights/year

Because unwashed airplanes can experience up to 0.1 percent increase in drag, poorer fuel mileage can be expected relative to clean airplanes (see fig. 4). As a result, one of the easiest, most cost-efficient steps an airline can take to save fuel costs is to maintain clean airplanes. Periodic washing of airplane exteriors also minimizes metal corrosion and paint damage, aids in locating leaks and local damage, and improves the aesthetics of the airplane, enhancing the airline's image with the traveling public.

RECOMMENDATIONS

Boeing research supports the conclusion that use of external surface finish coatings should be based on surface protection properties and airplane cleanliness, not drag reduction. There is no plausible engineering explanation to justify a drag reduction beyond approximately 0.1 percent, nor is there conclusive test data. Boeing wind tunnel data confirm that the production surface finish of Boeing commercial airplanes are hydraulically smooth, meaning that further surface smoothness would not result in a measurable drag reduction.

The most effective means of in-service drag avoidance is maintenance of seals, surface fit and fair, and movable surface rigging (i.e., doors, control surfaces, high-lift devices). In addition, careful management of airplane loading to minimize trim drag can also be an effective means of reducing fuel consumption.

SUMMARY

Airlines are seeking ways to lower fuel consumption. One way is by reducing the drag caused by surface roughness. Boeing research has shown that surface coatings should not materially reduce drag, and that the most effective means of reducing drag is to maintain aerodynamically clean airplanes.

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