Frasers Aerospace

Fuel Economy Files

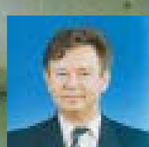
Prepared by Kevin Bishop

GETTING HANDS-ON EXPERIENCE WITH AERODYNAMIC DETERIORATION

This article is an extract of a brochure of the same name which covers the complete Airbus aircraft family.

Today's tough competitive environment forces airlines to reduce their operational costs in every facet of their business. Every method to achieve this goal has to be envisaged, safety and accident prevention permitting of course, as these are prime factors in any aircraft operation. A wide variety of different aspects have to be taken into account in this process, such as Air Traffic Control, engine deterioration, flight operations management, instrument accuracy or aero-dynamic deterioration.

The purpose of this document is to examine the influence of aerodynamic de-terioration.



by Jean-Jacques Speyer
Manager Operational Evaluation
Flight Operations Support
Airbus Industrie
Customer Services Directorate

The manufacturer does its best from the development phase onwards to foresee all potential deteriorations and adopt designs which are the least sensitive to in-service deterioration and by continuous research and modification programmes, to keep the aircraft deterioration processes within acceptable bounds. The operator's responsibility is to maintain his aircraft in good condition and make sure that it is utilised in the most satisfactory conditions possible.

Unfortunately, in the life of an aircraft , degradation is likely to occur. An aircraft is normally expected to increase its drag by up to 2% within five years if not properly maintained. Indeed, many aerodynamic elements may increase drag and their cumulative effect can introduce a significant cost increase. Simply adopting corrective action in order to repair these items, could lead to excessive maintenance costs. Therefore, the effect of deterioration has to be traded-off against the estimated maintenance cost, in order to check whether it is cost-effective to carry out corrective measures. Cost-benefit analysis is the only practical way of keeping an aircraft operationally efficient.

Airbus Industrie has carried out numerous performance audits in co-operation with airlines which, implicitly, have made a very useful contribution to this document.

The information in this document will help the aircraft operator adapt its maintenance programme, balancing financial aspects, such as increased fuel consumption against maintenance costs. It should enable operators to determine whether corrective actions are financially pertinent, despite short-term maintenance costs. Considerable longer-term expense may thus be avoided at relatively low cost. And strategic maintenance actions rather than detailed, dispersed and costly repair jobs may be more easily decided upon and justified.

GENERAL

Aerodynamic deterioration

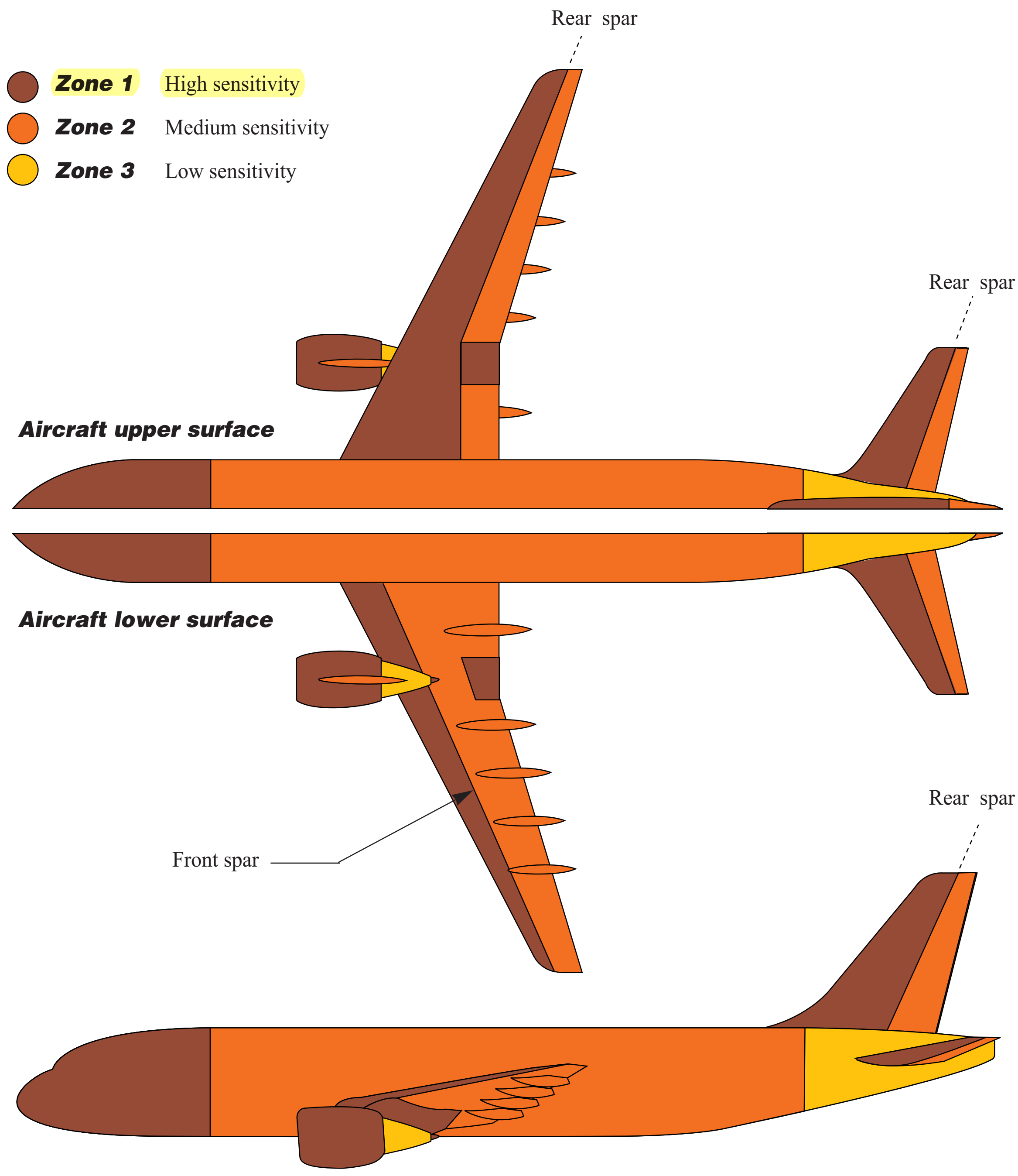
Some of the most severe penalties in terms of fuel consumption are caused by increased drag resulting from poor airframe condition. Normal aerodynamic deterioration of an aircraft over a period of time can include the incomplete retraction of moving surfaces, damaged seals on control surfaces, skin roughness and deformation due to bird strikes or damage caused by ground vehicles, chipped paint, mismatching doors and excessive gaps. All these items are potential money wasters. Each deterioration incurs drag increase, and this increased drag is accompanied by increased fuel consumption.

Sensitivity classification

The fuel burn penalty caused by drag-inducing items is largely dependent upon the location and extent of the problem; different areas of the airframe are more or are less sensitive to alterations in their optimum aerodynamic smoothness. Bearing this in mind, a zonal classification can be established for drag sensitivity over the whole aircraft (see Figure 1).

Zone 1 surfaces require high aerodynamic smoothness because they are endowed with high local flow velocities and very thin boundary layers which are very sensitive to small local disturbance. Zone 3 surfaces are much less sensitive because of lower flow veloci-

Figure 1
Drag sensitivity zones (A300/A310)



ties and thicker boundary layers, and disturbance on these parts of the airframe does not produce high aerodynamic resistance to the airflow. Also, the transition from laminar to turbulent boundary layers having occurred earlier, zone 3 is less sensitive to aerodynamic irregularities or excrescences. Finally, zone 2 surfaces represent an average between these two extremes.

The localisation of zones 1, 2 and 3 for A300/A310 are shown in the figure 1. The zones differ slightly for the other Airbus aircraft.

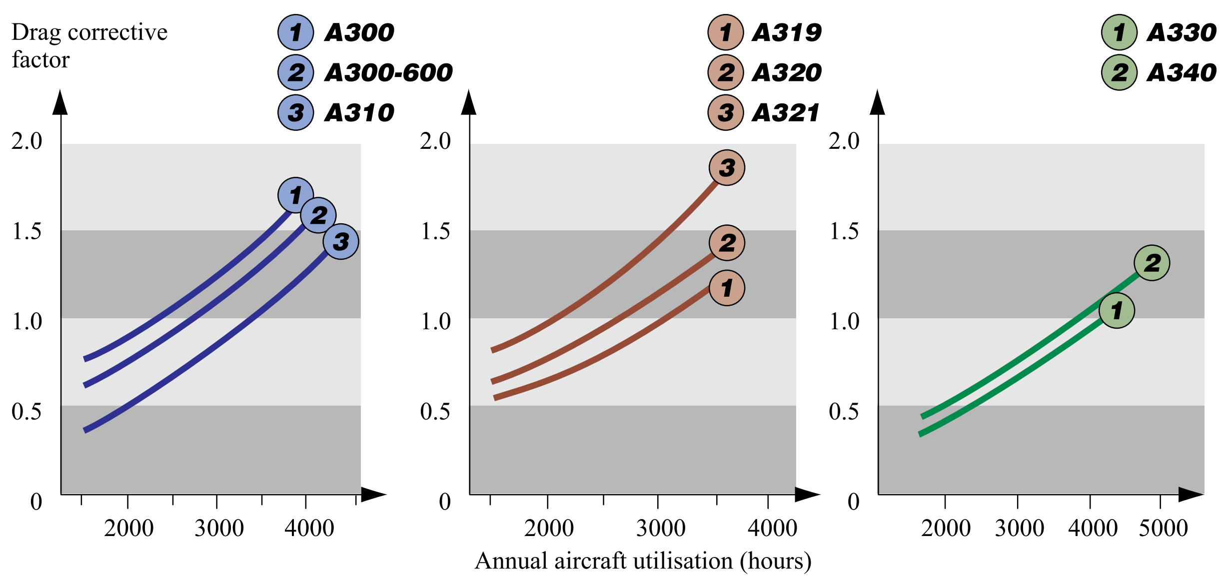
Fuel penalty calculation

It is possible to determine drag increase, generated by particular items, with wind-tunnel measurements or analytical techniques. The drag increase is then converted into terms of increased fuel burn - in US gallons per year per aircraft - but the reader must keep in mind that the values given correspond to an aircraft which is in accordance with specific assumptions. These assumptions refer to each type of aircraft of the three Airbus families and include annual flight hours based on airline statistics.

The drag increase can also be expressed in US$ per year per aircraft, the fuel price being based at US$0.60 per gallon. Note: fuel prices have increased by about 30% in the last year. Since calculation assumptions may vary significantly among individual operators, tables giving a corrective factor - to apply to the fuel penalty to be derived from the operator's annual flight hours - is given for each type of aircraft, in Figure 2.

Figure 2

Corrective factor for drag penalty



Airframe maintenance

For a specific corrective task, manhours required can significantly vary from one airline to another, and from one type of repair to another. The calculation method adopted in this document is simply an estimation partly based on measurements. These tasks should have been carried out assuming a regularly maintained aircraft, operated under normal conditions and with an average daily utilisation, having maintenance /corrective actions carried out in a hangar with good environmental conditions. All necessary standard and special tools, as well as ground support equipment, skilled maintenance personnel and appropriate maintenance documentation should also be available.

The values presented herein (men and manhours) are based on these assumptions and are intended to reflect operational reality as closely as possible.

Total maintenance costs, for both on-aircraft and shop tasks, include overhead and burden costs for maintenance planning, engineering orders, safety equipment, facilities and supervision. An acceptable rate per manhour covering all these aspects is US$50. Serving as a benchmark, this value corresponds to an average cost covering skilled working personnel.

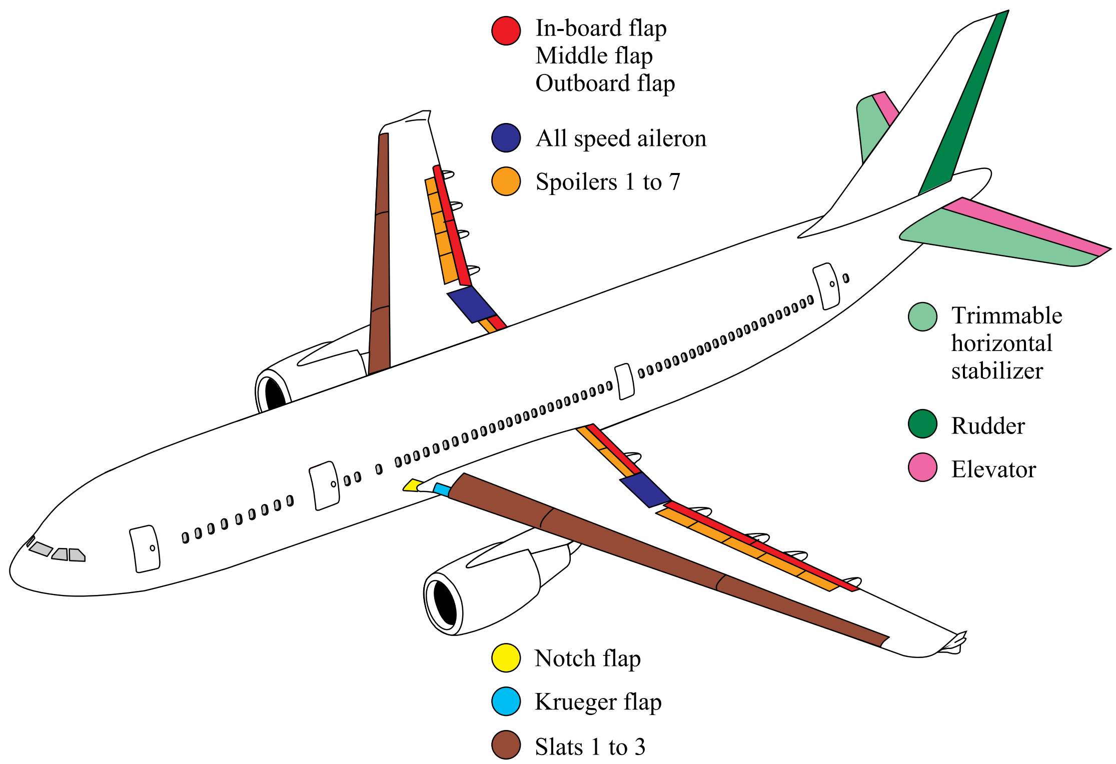
Adapted maintenance programme

As stated above, the degradations that are likely to occur stem from two main sources (excluding incidents or handling) : either mechanical wear or corrective actions which have not been properly executed. Although ill-considered or superficial repair may have negligible effect on performance, some tasks have to be carried out with special care, given their positive impact on fuel consumption.

As mentioned before, despite the efforts of maintenance organisations and manufacturers, deterioration can occur. It may have significant effects on consumption in spite of having only a slight influence on drag. One way to determine these effects is to use the Aircraft Performance Monitoring (APM) software. This programme calculates deviations in Specific Range and, to some extent, helps to determine how much these discrepancies stem from engine degradation and how much from a lack of aerodynamic cleanliness. Inherently, the program does not really differentiate between apparent and real drag.

Figure 3

Flying control surfaces



For instance, higher drag may be concluded from APM results but could, in fact, reflect lower thrust at N1 (or EPR). Also bleed leaks can affect apparent aerodynamic deterioration through N1 deviations by biasing the N1/thrust relationship if they are not accounted for. For these reasons, values given by the APM software have to be considered with great care.

Nevertheless, they can trigger an alarm at a predetermined loss of Specific Range in relation to the initial aircraft drag condition, and an unscheduled check could be launched to detect the type and location of any drag rise. This unscheduled check could be a line check walkaround associated with an overwing in-flight check observing and photographing control surfaces, preferably by means of a telephoto or zoom lens. The association of both types of check constitutes an Aerodynamic Inspection. The items to be observed are shown in Figure 3. This Aerodynamic Inspection, which would take only a short time to perform, should be done by skilled personnel as for example aerodynamics or performance engineers, able to interpret secondary effects (e.g. leakages) and to determine the corresponding deviations (as well as being able to conduct performance audits).

When both the type and extent of the deterioration are known, the following tables (example shown on Figure 4 on the following page)could be used to determine what should be repaired and what may be ignored, for financial reasons. Repair times should be scheduled during night-time periods, time permitting, otherwise the task has to be included in a scheduled check.

The Aircraft Performance Monitoring software has the advantage of potentially triggering an Aerodynamic Inspection just when it is needed, thus avoiding unnecessary inspection.

If the APM software is not used, the Aerodynamic Inspection could be scheduled, for instance, at the occasion of a “C check”.

Although this approach may confirm discrepancies, not all may be identified. In this case direct measurements in the suspected area should be made, such as prescribed in the Aircraft Maintenance Manual. This second way is more expensive but it may offer better drag reduction results.

In a third stage, if the drag reduction seems insufficient, the airline may then ask Airbus Industrie for a Performance Audit.

These three approaches should help any airline to alleviate excessive fuel consumption.

Figure 4

Cost of misrigged flying control surfaces (A300/A310)

Control surface	Penalty in US$ gallons per year — Excess gap 5mm	10mm	15mm	Penalty in US$ per year — Excess gap 5mm	10mm	15mm	Aircraft Maintenance Manual	Corrective action — Men	M/h	Cost (US$)
Slat 1 (per metre)	3,850	6,100	9,150	2,310	3,660	5,490	27 80 00 27 81 00	2	5	250
Slat 2 (per metre)	5,190	8,220	12,330	3,110	4,930	7,400	27 80 00 27 81 00	2	5	250
Slat 3 (per metre)	7,700	12,200	18,300	4,620	7,320	10,980	27 80 00 27 81 00	2	5	250
Flap	810	1,490	2,060	490	890	1,230	27 51 00 27 54 00	2	6	300
Spoiler	3,060	6,850	10,220	1,840	4,110	6,130	27 61 00 27 62 00	1	2	100
Aileron	810	1,500	2,120	490	900	1,270	27 11 00	1	3	150
Rudder	1,350	2,350	3,550	810	1,410	2,130	27 21 00 27 24 00	2	4	200
Misalignment at flap track fairing	680	1,360	1,700	410	820	1,020	05 25 30	2	5	250

DETERIORATION OF AIRFRAME AND SURFACES

The purpose of the following is to give a fuel penalty and maintenance cost comparison for the items studied.

Values given in this particular section correspond to the smaller fuel penalties applicable to all Airbus Industrie aircraft. They are intended to make the reader more sensitive to fuel penalties / maintenance cost comparison and to sort out a few general conclusions which pertain to all Airbus Industrie aircraft.

Misrigging of control surfaces.

These items correspond to specific control surfaces misrigging (see Figure 5). They incur one of the largest fuel penalties, while the cost of the corrective actions, by comparison, is negligible. Indeed, one spoiler extended by 15mm over a 1 metre spanwise length leads to more than US$ 6,000 penalty per aircraft per year (see Figure 4 above). Similarly, an outboard slat misrigging causes nearly US$ 11,000 penalty per aircraft per year. Furthermore, flap misrigging - or especially rudder misrigging - can lead to a slightly lower, but still considerable, fuel penalty. Another sensitive item which is generally forgotten is misalignment at a flap track fairing which may cost nearly US$ 1,000 per aircraft per year.

The Aerodynamic Inspection could be done in flight, simply by a visual inspection from the passenger compartment and by photographing control surfaces by means of a telephoto or zoom lens.

For a misrigged control surface, the associated corrective action cost is negligible and should indeed be undertaken.

Absence of seals on movable sections

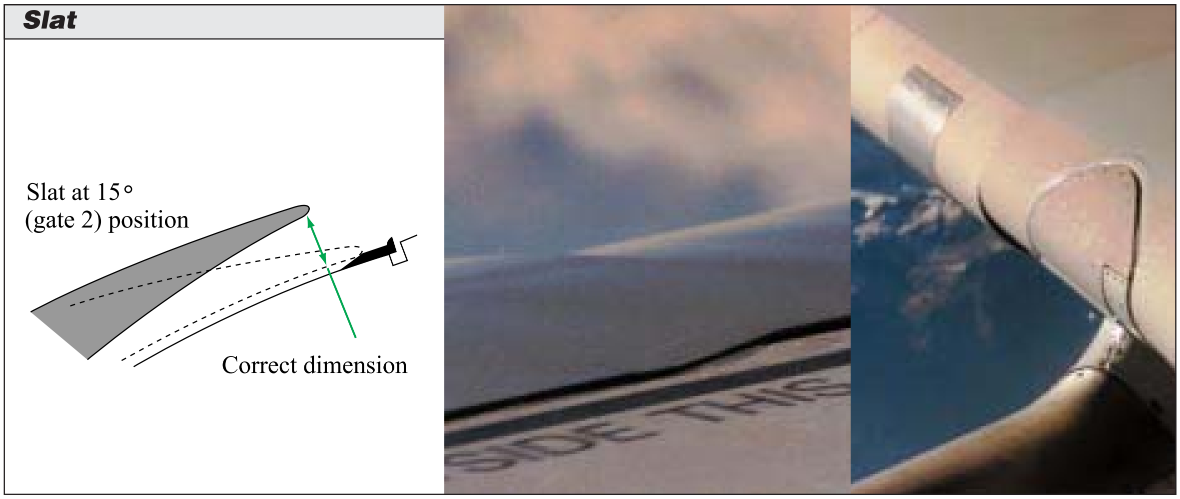
Seals on movable sections are very important and should not be forgotten. The spanwise slat seals are mandatory for the optimisation of the wing supercritical airfoil. One metre of missing seal incurs a penalty of US$ 2,300 per aircraft per year. The chordwise flap seal, which may seem to have a rather negligible effect, causes more than US$ 3,000 extra cost per aircraft per year. However, the worst penalty would result from a missing fairing

Damaged chordwise flap seal

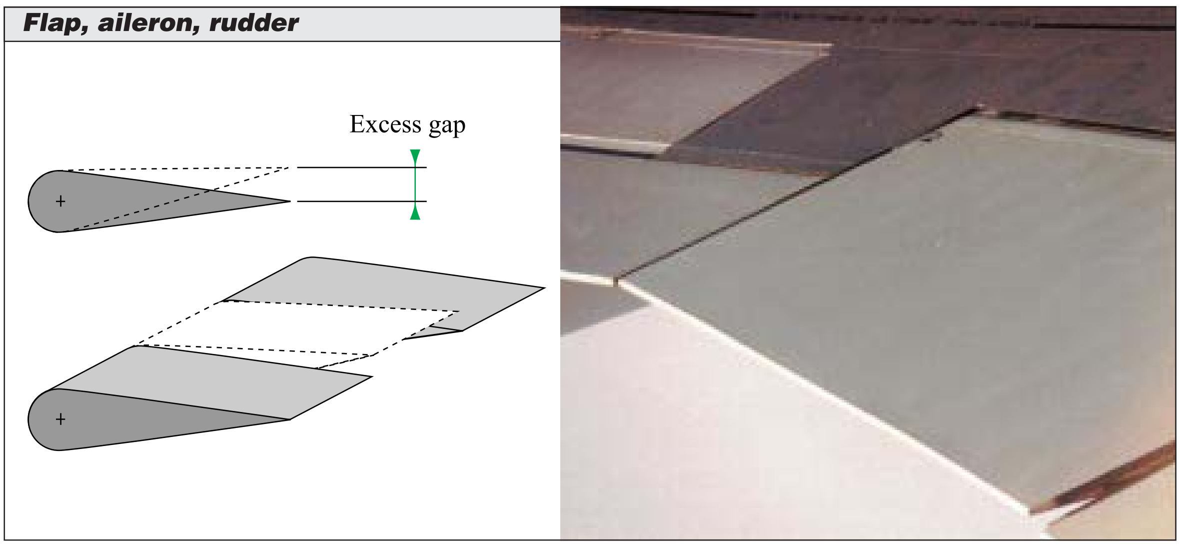
Figure 5

Misrigging of control surfaces

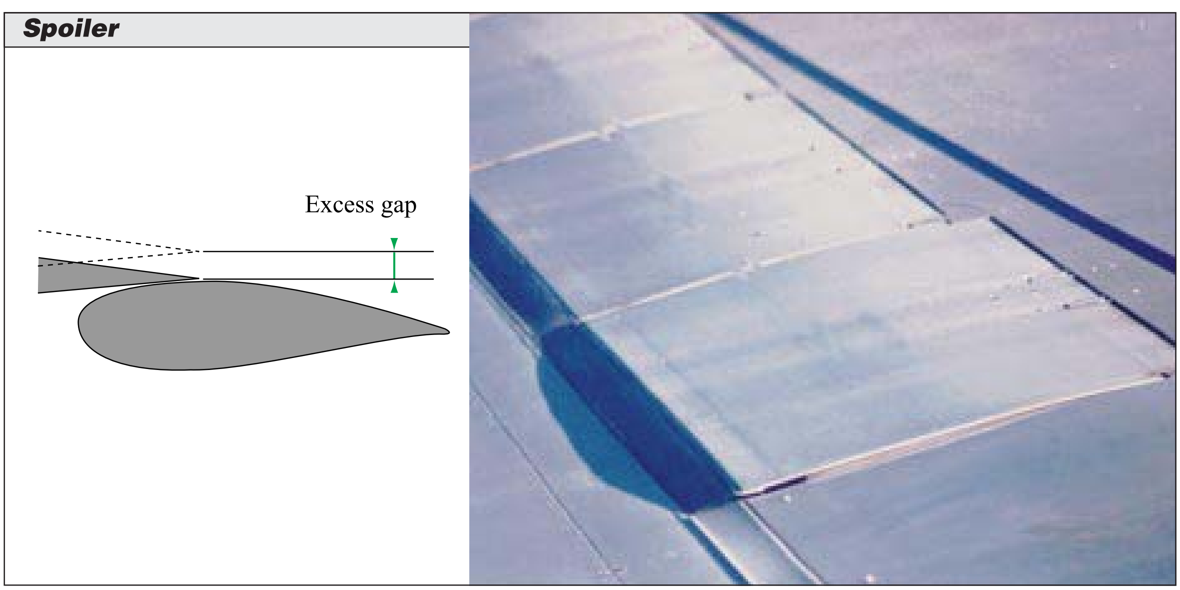
Slat



Flap, aileron, rudder



Spoiler



and rubber seal at the fin/fuselage junction (US$ 3,500).

The check can be done from the ground during the Aerodynamic Inspection, preferably with extended control surfaces. With retracted control surfaces, the same check could be done by analysing leakage traces on the wing surface below the seals.

The associated corrective action costs are negligible and such action should be scheduled.

Missing parts

Missing parts are given in the Configuration Deviation List showing missing parts which must be replaced as soon as possible. A missing access door can cost over US$ 6,000 per year which provides adequate motivation to minimise the period of loss.

Mismatched doors

Mismatched access door

A step on the forward fuselage surface is much more penalising than one on the rear. Misalignment of forward doors must be monitored very carefully; a 10mm forward cargo door step imposes a US$ 2,300 annual penalty, although the associated corrective action costs US$ 650.

During the Aerodynamic Inspection, the door can be checked by standing under it and observing the line where it meets the fuselage. Due to pressurisation, the cabin door must be slightly out of flush with the fuselage. In other words, the door must be 2-3 mm inside the fuselage when checked on the ground (see Maintenance Manual).

The decision - to repair or not - is not easy, knowing that an estimated rigging cost could be much higher, especially if insufficiently skilled personnel are available.

The decision is a matter of judgement by each operator.

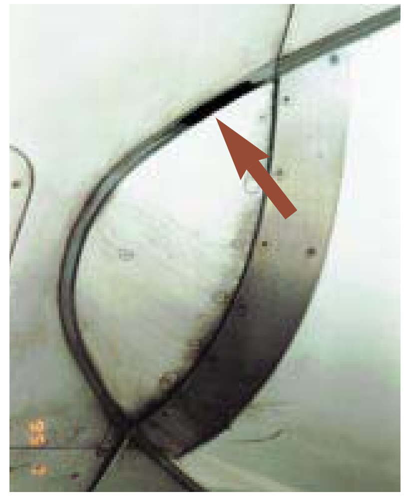
Missing door seal section

A missing door seal section has two effects: it disturbs the external flow and causes a slight leakage which has to be compensated for by an increase in engine compressor air bleed. In addition to the fuel penalty, a stress-provoking low-frequency whistling sound is audible in the cabin which could possibly annoy passengers.

Preferably, the inspection should be done with the door opened, looking for damaged sections of the seal. With a closed door, the same verification could be done simply by analysing dirt traces on the fuselage.

Since this leakage may increase with time, even if corrective actions are quite expensive, this work should be implemented to remove the risk of further deterioration which would lead to the aircraft being grounded eventually.

Missing seal

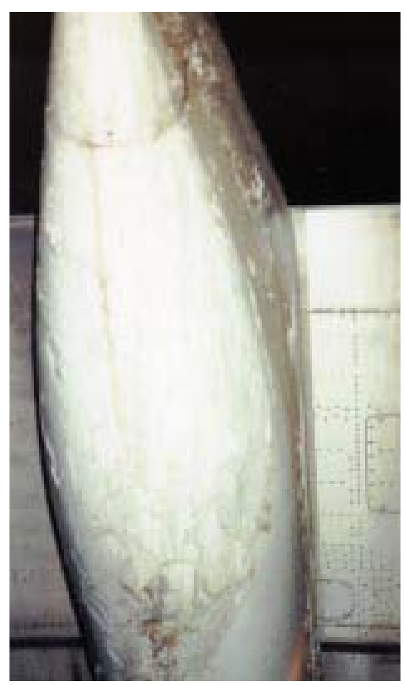


Surface deterioration

Skin roughness

Surface deterioration can lead to significant fuel penalties, especially if the skin is rough or dirty. For a complete aircraft - in the worst case - the penalty can be as high as US$ 60,000 per aircraft per year. Another serious penalty would certainly be on the airline's commercial image!

Skin roughness



Skin dents

Simple dents also cause some fuel penalty which are not costly in terms of fuel consumption (US$ 100 per aircraft per year in the worst case) but are very expensive to repair. If the dent is within the Structural Repair Manual tolerances, no action is necessary for purely aerodynamic reasons.

With repeated «loaders' assaults», scuff plates are frequently dented and generally present a step, generating high fuel penalties, but corrective actions are not particularly time-consuming.

Unfilled butt joint gap

Unfilled butt joint gaps in aircraft skins are not very expensive in terms of excess fuel consumption (US$22 per aircraft per year in the worst case).

CONSEQUENCES OF HASTY REPAIRS

Sometimes, in an operational environment, the purpose of a repair is simply to keep the aircraft in service and to avoid grounding it. Repairs may have been done without taking into account the consequences of increased fuel consumption.

Overfilled butt joint gap

If a butt joint gap is overfilled, the penalty can be significant on the wing upper surface (US$330). A repair which is not properly carried out can lead to a heavier fuel penalty than existed prior to the repair (from US$14 per aircraft per year for an unfilled butt joint gap to US$500 for an overfilled gap on the upperwing in the sensitive zone 1).

External repairs

In the same way, external patches induce more drag, especially on the wing upper surface (US$640). It is normally difficult to replace an external patch by an internal one, but if access has already been gained during an inspection, installing an internal patch could be preferable, since it also has less impact on an airline's commercial image.

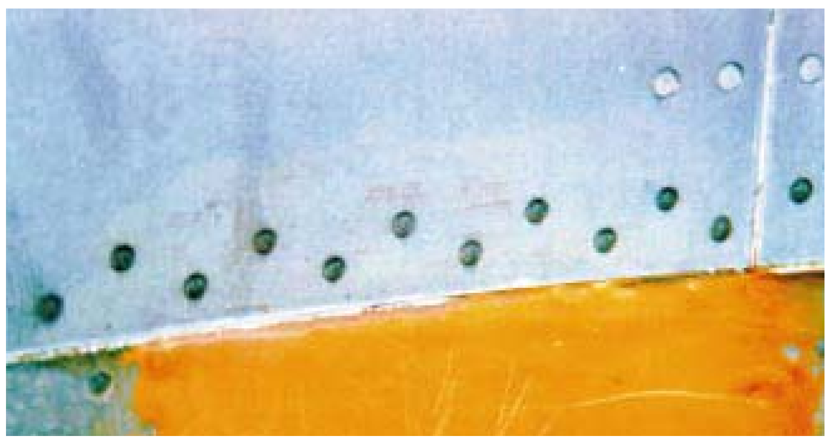
Paint peeling

On the other hand, for visually improving the commercial image, some fleets are often hastily repainted without bothering to properly prepare the surface. Additional paint layers cause increased aircraft weight and the surface is less smooth due to paint steps. Over a short time, paint may peel, with dramatic drag effects, and severe risk of corrosion.

In order to prevent paint problems, proper preparation has to be carried out before any refresher coat is applied.

Manhours for painting have also to be determined with great care because ground time due to paint drying has much more effect on aircraft operation than the simple manhour cost by itself.

Dented scuff plates



External repair

Paint peeling

ENGINE COWLING

The engine cowling, due to its location in a very sensitive zone, has to be observed with great care during the Aerodynamic Inspection.

All surface discrepancies incur considerable drag .

Another item, which is less obvious because it is hidden, is the reverser door seal. The associated fuel penalty is very large and it can be observed by leakages on the engine cowling.

CONCLUSION

The purpose of presenting the foregoing examples is simply to make operators and maintenance personnel more aware of drag-induced performance degradation on normal day-to-day operation.

Manhours for structural repairs must be determined with great care because significant differences exist, mainly depending upon the exact location of the deterioration. All these discrepancies can be observed very easily from the ground during the Aerodynamic Inspection.

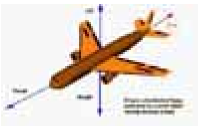
It has been shown that many, but not all, aerodynamic degradations can be easily detected and cost-effectively repaired. The Aerodynamic Inspection will identify all of these degradations.

It ultimately becomes a matter of judgement for the airline to decide whether to rectify a fault or to ignore its effect. Nevertheless, all maintenance and operations personnel should be aware of fuel penalties which may stem from misrigged control surfaces, defective seals and the lack or aircraft cleanliness - especially at or near leading edges and forward sections of the aircraft.

Airbus Industrie is convinced that prevention is better than repair. Continuously monitoring aircraft aerodynamic efficiency, together with timely rectification of problems, is, without a doubt, the best approach to minimising unnecessary fuel consumption.

For copies of the complete document, please contact AIRBUS INDUSTRIE headquarters, Customer Services Directorate, Flight Operations Support Department, Mr Jean-Jacques Speyer, Manager Operational Evaluation
1, rond-point Maurice Bellonte, 31707 BLAGNAC Cedex - Tel: +33 (0)5 61 93 30 02 / 30 91 - Fax: +33 (0)5 61 93 29 68 / 44 65

Drag

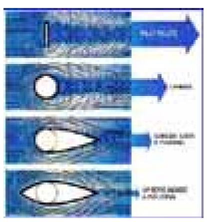


Drag is a resistance force generated by a solid object moving through a fluid.

Any physical body being propelled through the air has drag associated with it. In aerodynamics, drag is defined as the force that opposes forward motion through the atmosphere and is parallel to the direction of the free-stream velocity of the airflow. Drag must be overcome by thrust in order to achieve forward motion.

Drag is generated by nine conditions associated with the motion of air particles over the aircraft. There are several types of drag: form, pressure, skin friction, parasite, induced, and wave.

The term "separation" refers to the smooth flow of air as it closely hugs the surface of the wing then suddenly breaking free of the surface and creating a chaotic flow. The second picture on the left hand margin of this page shows examples of air flowing past a variety of objects. The bottom shows well behaved, laminar flow (flow in layers) where the flow stays attached (close to the surface) of the object. The object just above has a laminar flow for the first half of the object and then the flow begins to separate from the surface and form many chaotic tiny vortex flows called vortices. The two objects just above them have a large region of separated flow. The greater the region of separated flow, the greater the drag. This is why airplane designers go to such effort to streamline wings and tails and fuselages — to minimize drag.



Form or pressure drag is caused by the separation of air that is flowing over the aircraft or airfoil.

Form drag and *pressure drag* are virtually the same type of drag. Form or pressure drag is caused by the air that is flowing over the aircraft or airfoil. The separation of air creates turbulence and results in pockets of low and high pressure that leave a wake behind the airplane or airfoil (thus the name pressure drag). This opposes forward motion and is a component of the total drag. Since this drag is due to the shape, or form of the aircraft, it is also called form drag. Streamlining the aircraft will reduce form drag, and parts of an aircraft that do not lend themselves to streamlining are enclosed in covers called fairings, or a cowling for an engine, that have a streamlined shape. Airplane components that produce form drag include (1) the wing and wing flaps, (2) the fuselage, (3) tail surfaces, (4) nacelles, (5) landing gear, (6) wing tanks and external stores, and (7) engines.

Skin friction drag is caused by the actual contact of the air particles against the surface of the aircraft. This is the same as the friction between any two objects or substances. Because skin friction drag is an interaction between a solid (the airplane surface) and a gas (the air), the magnitude of skin friction drag depends on the properties of both the solid and the gas. For the solid airplane, skin fiction drag can be reduced, and airspeed can be increased somewhat, by keeping an aircraft's surface highly polished and clean. For the gas, the magnitude of the drag depends on the viscosity of the air. Along the solid surface of the airplane, a boundary layer of low energy flow is generated. The magnitude of the skin friction depends on the state of this flow.

The leading edge of a wing will always produce a certain amount of friction drag.

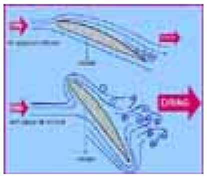
Parasite drag is simply the mathematical sum of form drag and skin friction drag.

Parasite Drag = Form Drag + Skin Friction Drag

Induced drag is the drag created by the vortices at the tip of an aircraft's wing. *Induced drag* is the drag due to lift. The high pressure underneath the wing causes the airflow at the tips of the wings to curl around from bottom to top in a circular motion. This results in a trailing vortex. Induced drag increases in direct proportion to increases in the angle of attack. The circular motion creates a change in the angle of attack near the wing tip which causes an increase in drag. The greater the angle of attack up to the critical angle (where a stall takes place), the greater the amount of lift developed and the greater the induced drag.

All of these types of drag must be accounted for when determining drag for subsonic flight. The *total drag* is the sum of parasite and induced drag.

Total Drag = Parasite Drag + Induced Drag

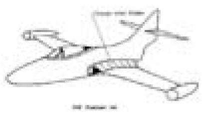


Induced drag is a byproduct of lift.

But the net (or total) drag of an aircraft is not simply the sum of the drag of its components. When the components are combined into a complete aircraft, one component can affect the air flowing around and over the airplane, and hence, the drag of one component can affect the drag associated with another component. These effects are called *interference effects*, and the change in the sum of the component drags is called *interference drag*. Thus,

$$(\text{Drag})_{1+2} = (\text{Drag})_1 + (\text{Drag})_2 + (\text{Drag})_{\text{interference}}$$

Generally, interference drag will add to the component drags but in a few cases, for example, adding tip tanks to a wing, total drag will be less than the sum of the two component drags because of the reduction of induced drag.



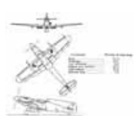
This figure shows a Grumman F9F Panther Jet with a large degree of filleting to reduce drag.

Interference drag can be minimized by proper fairing and filleting, which induces smooth mixing of air past the components. No adequate theoretical method will predict interference drag; thus, wind tunnel or flight-test measurements are required. For rough computational purposes, a figure of 5 percent to 10 percent can be attributed to interference drag on a total aircraft.

Small items also add to the total aircraft drag and, although seemingly trivial, they can greatly reduce the aircraft's top speed.

Although prediction of drag and wind tunnel drag measurements of models yield good results, final drag evaluation must be obtained by flight tests.

Wave drag occurs in supersonic flight, or flight above the speed of sound. Wave drag is a form of pressure drag. When an aircraft breaks the speed of sound, a shock wave is created. A shock wave is a strong pressure wave that creates a violent change in pressure. High pressure pushes on the front of the aircraft. This results in a large pressure drag toward the rear of the aircraft like that produced with form or pressure drag in subsonic flight.



This figure shows a Me-109G German fighter from World War II. Shown is the percentage breakdown of the drag (includes interference drag) of the components.

The airplane's total drag determines the amount of thrust required at a given airspeed. Thrust must equal drag in steady flight.

Lift and drag vary directly with the density of the air. As air density increases, lift and drag increase and as air density decreases, lift and drag decrease. Thus, both lift and drag will decrease at higher altitudes.

The equation used to calculate drag is:

$$D = \tfrac{1}{2} \rho V^2 S C_D$$

Where:

ρ - the density of the air

V - velocity of the air (air speed)

S -surface area of the aircraft

C_D - coefficient of drag

Decrease in airplane drag coefficient with time.

The coefficient of drag is calculated based on the angle of attack and shape of the aircraft. The angle of attack is the angle between the direction of the wing (chord line) and the relative wind of the aircraft.

—Dan Johnston

References and Further Reading:

Anderson, Jr., John D. *A History of Aerodynamics*. Cambridge, England: Cambridge University Press, 1997.

Montgomery, Jeff, exec. ed. *Aerospace: The Journey of Flight*. Maxwell Air Force Base, Ala.: Civil Air Patrol: 2000.

Smith, Hubert "Skip." *The Illustrated Guide to Aerodynamics*. 2nd edition. Blue Ridge Summit, Pa.: Tab Books Inc.1992.

Talay, Theodore A. *Introduction to the Aerodynamics of Flight*. SP-367, Scientific and Technical Information Office, National Aeronautics and Space Administration, Washington, D.C. 1975. Available at http://history.nasa.gov/SP-367/cover367.htm.

Wegener, Peter P. *What Makes Airplanes Fly?* New York: Springer-Verlag, 1991.

"Boundary Layer Separation and Pressure Drag." University of Virginia Department of Physics. http://www.phys.virginia.edu/classes/311/notes/fluids2/node11.html

"Drag." Lego Design and Programming System. http://ldaps.ivv.nasa.gov/Physics/drag.html

"Streamlining." http://www.grc.nasa.gov/www/K-12/airplane/stream.html

"Angle of attack." http://wright.grc.nasa.gov/WWW/K-12/airplane/incline.html

"Speed of sound." http://wright.grc.nasa.gov/WWW/K-12/airplane/sound.html

"Shock Waves." Encyclopedia Britannica. http://www.britannica.com/eb/article?eu=69210&tocid=0&query=shock%20wave. Available on CD, on-line through subscription, and in print version.

"What Is Drag?" NASA Glenn Research Center. http://www.grc.nasa.gov/WWW/K-12/airplane/drag1.html.

Educational Organization	Standard Designation (where applicable	Content of Standard
International Technology Education Association	Standard 2	Students will develop an understanding of the core concepts of technology.
National Council of Teachers of Mathematics	N/A	Understand the value and use of mathematical language.
National Council of Teachers of Mathematics	N/A	Understand numbers, ways of representing numbers, relationships among numbers, and number systems.
American Association for the Advancement of Science	N/A	Understand principles of motion and forces

getting to grips with

fuel economy

Issue 3 - July 2004

Customer Services

AIRBUS

Flight Operations Support & Line Assistance

Customer Services
1, rond-point Maurice Bellonte, BP 33
31707 BLAGNAC Cedex FRANCE
Telephone (+33) 5 61 93 33 33
Telefax (+33) 5 61 93 29 68
Telex AIRBU 530526F
SITA TLSBI7X

getting to grips with

fuel economy

Issue 3 - July 2004

AIRBUS

TABLE OF CONTENTS

1. SUMMARY

Fuel Consumption is a major cost to any airline, and airlines need to focus their attention on this in order to maintain their profitability. This brochure looks at all the significant operating variables that affect fuel economy for the current Airbus range of aircraft.

This brochure shows that there are many factors that affect fuel consumption and that the potential gains and losses are huge. Most of these factors are directly controlled by the airlines own employees (flight crew, operations/dispatch, maintenance, etc.).

It can be also seen that what is good for one type of aircraft is not necessarily good for another, and that certain conceptions regarding best techniques for fuel economy are wrong.

Finally for a fuel and cost economic airline, the following are the main features:

- Good flight planning based on good data.
- Correct aircraft loading (fuel weight and CG).
- An aerodynamically clean aircraft.
- Optimal use of systems (APU, Bleed, Flaps/Slats, Gear, etc).
- Flight Procedures using speeds and altitudes appropriate to the companies economic priorities.
- Use of the FMGS in the managed mode.
- Use of performance factors in flight planning and in the FMGS derived from an ongoing aircraft performance monitoring program.

2. PREAMBLE

The very competitive and deregulated aviation market as well as the fear of a fuel price rise have made airlines understand how important it is to work on the fuel consumption of their fleet. Indeed airlines try to reduce their operational costs in every facet of their business, and fuel conservation has become one of the major preoccupations for all airlines, as well as aircraft manufacturers. That's why all ways and means to reduce fuel costs have to be envisaged, safety being of course the number one priority in any airline operation.

The purpose of this document is to examine the influence of flight operations on fuel conservation with a view towards providing recommendations to enhance fuel economy.

It is very rare that the reduction of fuel used is the sole priority of an airline. Such instances are to maximize range for a given payload, or to decrease fuel uplift from a high fuel cost airport. Generally fuel is considered one of the direct operating costs and an airline tries to minimize total direct operating costs. This introduces the concept of Cost Index and is the scope of another brochure (Getting to Grips with the Cost Index). However it is sometimes necessary to consider the cost implication of a fuel economy, and this is done where necessary in this brochure.

This brochure systematically reviews fuel conservation aspects relative to ground and flight performance. Whilst the former considers center of gravity position, excess weight, flight planning, auxiliary power unit (A.P.U.) operations and taxiing, the latter details climb, step climb, cruise, descent, holding and approach.

None of the information contained herein is intended to replace procedures or recommendations contained in the Flight Crew Operating Manuals (FCOM), but rather to highlight the areas where maintenance, operations and flight crews can contribute significantly to fuel savings.

3. INTRODUCTION

This brochure considers the two flight management modes: "**managed**" mode and "**selected**" mode.

The **managed mode** corresponds to flight management by means of a dedicated tool, the flight management system (FMS). Crews interface through the multipurpose control and display unit (MCDU) introducing basic flight variables such as weight, temperature, altitude, winds, and the cost index. From these data, the FMS computes the various flight control parameters such as the climb law, step climbs, economic Mach number, optimum altitude, descent law. Hence, when activated, this mode enables almost automatic flight management.

When in managed mode, aircraft performance data is extracted from the FMS database. This database is simplified to alleviate computation density and calculation operations in the FMS, but individual aircraft performance factors can produce good correlation with actual aircraft fuel burns.

When in **selected mode**, crews conduct the flight and flight parameters such as speed, altitude, and heading have to be manually introduced on the flight control unit (FCU).

The **cost index (CI)** used in the managed mode provides a flexible tool to control fuel burn and trip time to get the best overall economics. A technique that reduces fuel burn often requires more trip time. Hence fuel savings are offset by time related costs (hourly maintenance costs, flight and cabin crew costs and marginal depreciation or leasing costs). The cost index is the cost of time ($/min) compared with the cost of fuel ($/kg) and is used to obtain the best economics.

If fuel costs were the overriding priority, because fuel costs were much more significant than the cost of time, then the cost index would be low. With zero cost of time it would be zero and the FMS would fly the aircraft at Mach for max range (MMR).

However if the cost of fuel was very cheap compared to the cost of time, then speed would be important and the CI would be high. For zero cost of fuel, the Cost Index would be 999 and the FMS would fly the aircraft just below MMO.

Best economics would be between these two speeds and would depend on the operator's cost structure and operating priorities. For more information on Cost Index see "Getting to Grips with the Cost Index"

4. PRE-FLIGHT PROCEDURES

Operation of the aircraft starts with the aircraft on the ground by aircraft maintenance, preparation and loading.

This part intends to highlight the impact of some ground operations on fuel consumption. Even if these operations enable only little savings in comparison with savings made during the cruise phase, ground staff has to be sensitive to them and should get into good habits.

This part is divided into seven different sections:

- Center of gravity position
- Excess Takeoff weight
- Flight Planning
- Ways of taxiing to save fuel
- Auxiliary Power Unit
- Fuel Tankering
- Aerodynamic Deterioration

4.1 CENTER OF GRAVITY POSITION

4.1.1 INTRODUCTION

The gross weight is the sum of the dry operating weight, payload and fuel and acts as one force through the center of gravity (CG) of the aircraft. The balance chart allows the determination of the overall center of gravity of the airplane taking into account the center of gravity of the empty aircraft, the fuel distribution and the payload. It must be ensured that the center of gravity is within the allowable range referred to as the center of gravity envelope.

A more forward center of gravity requires a nose up pitching moment obtained through reduced tail plane lift, which is compensated for by more wing lift. This creates more induced drag and leads to an increase in fuel consumption. It is better to have the center of gravity as far aft as possible. As a rearward shift in CG position deteriorates the dynamic stability of the aircraft, the CG envelope defines an aft limit.

4.1.2 AUTOMATIC CENTER OF GRAVITY MANAGEMENT

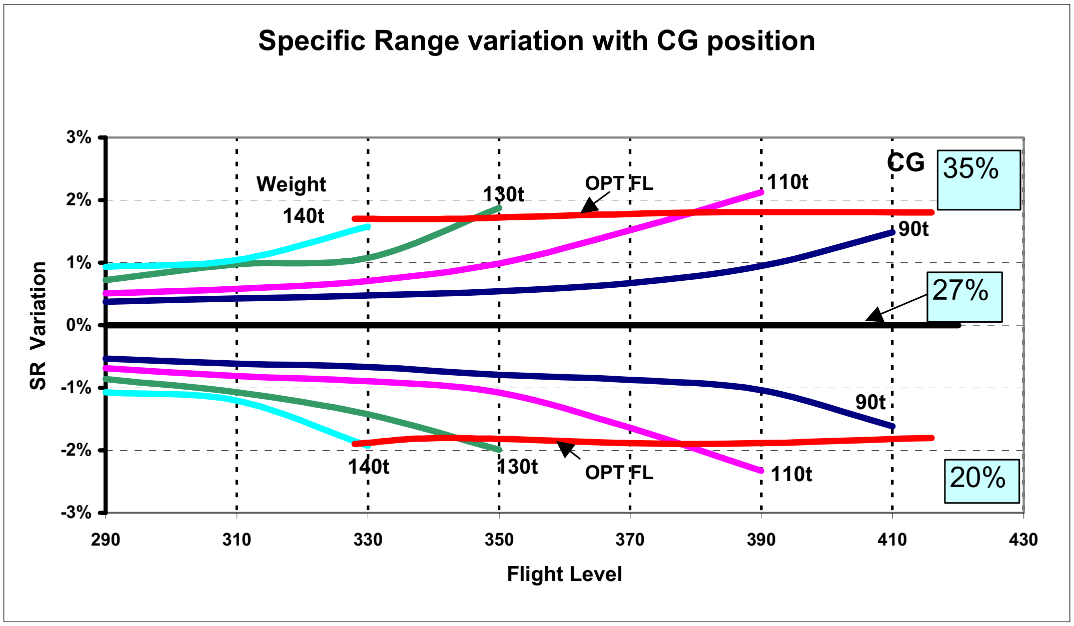
AIRBUS has created a trim tank transfer system that controls the center of gravity of the airplane. This system is installed on some A300 and A310 aircraft and all A330 and A340 aircraft. When an airplane with a trim tank is in cruise, the system optimizes the center of gravity position to save fuel by reducing the drag on the airplane. The system transfers fuel to the trim tank (aft transfer) or from the trim tank (forward transfer). This movement of fuel changes the center of gravity position. The crew can also manually select forward fuel transfer.

The Fuel Control and Management Computer (FCMC) calculates the center of gravity of the airplane from various parameters including input values (Zero Fuel Weight or Gross Take-off Weight and the associated CG) and the fuel tank contents. It continuously calculates the CG in flight. From this calculation, the FCMC decides the quantity of fuel to be moved aft or forward in flight to maintain the CG between the target value and 0.5% forward of the target band.

Usually one initial aft fuel-transfer is carried out late in the climb to bring the CG within this band. During the flight there are several smaller forward movements as the fuel burn moves the CG more aft. Finally a forward transfer is made as the aircraft nears its destination to bring the CG within the landing CG range.

4.1.3 INFLUENCE ON FUEL CONSUMPTION

The following graph shows the change in fuel consumption, expressed in terms of specific range (nm per kg of fuel), for both a Forward (20%) and an Aft (35%) CG position compared to a mid CG position of 27% at cruise Mach.



This graph, which is for the A310-203, shows the advantage of flying at aft CG. Also shown are the optimum altitude lines and these show the effects of CG to be constant at these altitudes, with almost no variation with aircraft weight. Other aircraft have similar shape curves with similar optimum altitude characteristics (except the A320 family). The following table summarizes the effect of CG on specific range at the optimum altitude :

Aircraft Type	Aft CG(35-37%)	Fwd CG(20%)
A300-600	+1.7%	-0.9%
A310	+1.8%	-1.8%
A330	+0.5%	-1.3%
A340	+0.6%	-0.9%

For the A300/A310 reference CG is 27% and aft CG is 35%.

For the A330/A340 reference CG is 28% and aft CG is 37%.

At maximum altitude, the change in fuel consumption given in the table is larger by up to 1%. However no benefit is obtained, as the specific range (SR) is lower at aft CG at maximum altitude than at mid CG at optimum altitude.

For aircraft that are not fitted with automatic center of gravity management, not all these advantages may be realized because of the normal forward and rearward shift of CG in flight due to fuel burn. In addition loading these aircraft at max fuel to an aft CG could prove difficult.

The **A320 family** does not show the same SR variation with CG as the other aircraft. The aft CG produces worst SR at FL290, crossing over to show an improvement at higher flight levels. The SAR variation is much smaller also. This is due to a complex interaction of several aerodynamic effects. The SAR can be considered effectively constant with CG position. Loading is therefore not critical for fuel economy for the A320 family.

In order to assess the overall impact of CG variation on fuel burn, it must be assessed on a complete sector. The following table shows increases in fuel consumed with a more forward CG. It is expressed as kg per 1000nm sector per 10% more forward CG for the max variation case (high weight, high flight level) with no in flight CG shift. The fuel increment in kg is also given for the Forward (20%) position, compared with the Aft (35 or 37%) position, for a typical sector.

Fuel Burn Increase with a more Forward CG

Aircraft types	Fuel increment KG/1000nm/10%CG	Typical Sector distance (nm)	Fuel increment per sector (kg)
A300-600	240	2000nm	710
A310	110	2000nm	330
A319/A320/A321	Negligible	1000nm	Negligible
A330-200	70	4000nm	480
A330-300	90	4000nm	600
A340-200	90	6000nm	900
A340-300	80	6000nm	800
A340-500	150	6000nm	1550
A340-600	130	6000nm	1300

4.2 TAKEOFF WEIGHT

4.2.1 INTRODUCTION

Another way to save fuel is to avoid excess take-off weight, which consists of the operating empty weight of the aircraft plus the payload plus the fuel.

In addition accurate knowledge of weight is an important factor needed to ensure that fuel burn predictions are met. This gives pilots confidence in the flight plans thus reducing the tendency to carry excess fuel.

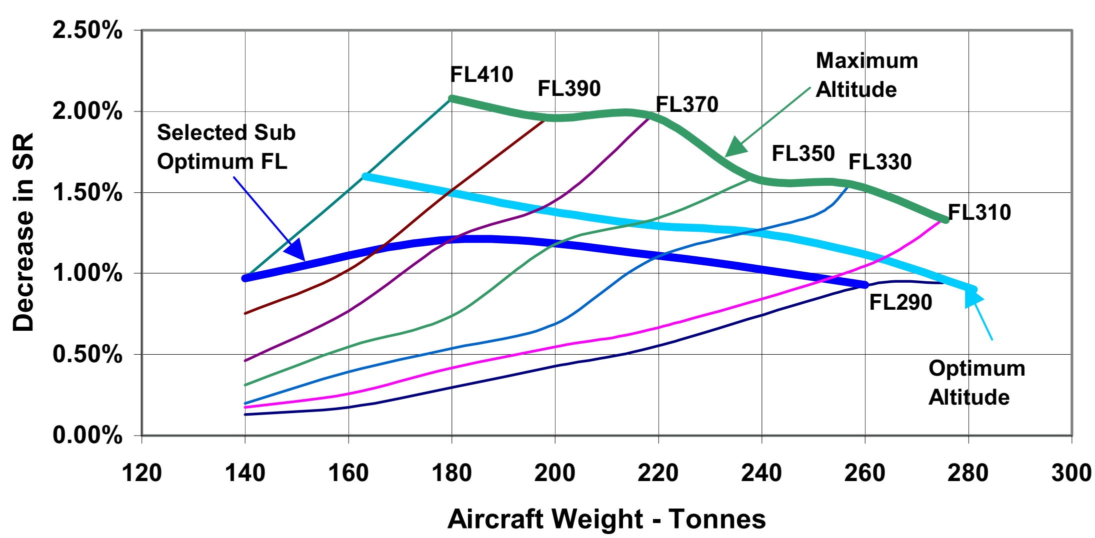
4.2.2 OVERLOAD EFFECT

The specific range, flying at given altitude, temperature and speed depends on weight. The heavier the aircraft, the higher the fuel consumption.

In addition, fuel savings can be made during climb since the aircraft would reach its optimal flight level earlier if it were lighter.

The effect of overloading with respect to the in-flight weight is shown on the following graph, for an excess load of 1% of MTOW (2600kg) in cruise for an A340-313 This shows the increase in specific range penalty with both weight and altitude. Maximum and optimum altitudes are shown together with selected sub optimum flight levels representing the choice of a FL below the Optimum instead of above it. For example, at 220t the optimum altitude is just under FL 350. If we select FL 330 1% extra MTOW will decrease the specific range by just under 1.2%

Specific Range Penalty for Excess Weight of 1% MTOW
A340-313 ISA MN 0.82



The characteristic curves for the other aircraft types have a similar shape. Calculating the weight effect on specific range on all Airbus aircraft in accordance with the lower boundary of typical flight levels gives an average reduction of 1% of SR for a weight increase of 1% of Maximum Take-off Weight. The scatter in this value is generally within .2%.

At the higher altitudes, obtainable at lower weights, the previous picture shows that the SR reduction can increase to 1.5%

Overloading affects not only the trip fuel but also the reserves and requires increased fuel uplift for a specific mission. The following table shows the effect of 1 tonne/1000nm and also 1% of basic MTOW for a typical sector, both at optimum altitude, assuming maximum passengers and some freight.

Aircraft types	Payload	Weight Increase	Stage	Fuel Penalty 1000nm/t	Fuel penalty per sector	Extra Reserves
A300-600	31000 kg	1705 kg	2000 Nm	93 kg	320 kg	100 kg
A310-300	26560 kg	1500 kg	2000 Nm	59 kg	240 kg	90 kg
A318	14650 kg	640 kg	1000 Nm	31 kg	30 kg	30 kg
A319	13000 kg	590 kg	1000 Nm	38 kg	50 kg	40 kg
A320	17200 kg	735 kg	1000 Nm	43 kg	60 kg	45 kg
A321	19100 kg	890 kg	1000 Nm	48 kg	55 kg	50 kg
A330-200	29800 kg	2300 kg	4000 Nm	49 kg	460 kg	100 kg
A330-300	29800 kg	2300 kg	4000 Nm	47 kg	440 kg	100 kg
A340-200	29000 kg	2535 kg	6000 Nm	74 kg	1130 kg	170 kg
A340-300	29000 kg	2535 kg	6000 Nm	87 kg	1330 kg	230 kg
A340-500	35700 kg	3680 kg	6000 Nm	64 kg	1410 kg	210 kg
A340-600	42250 kg	3650 kg	6000 Nm	65 kg	1420 kg	210 kg

Although the A320 family show considerably lower fuel burn penalties than the other aircraft, the total fuel penalty is of a similar order due to the high number of sectors per day. It can readily be seen that a 1% weight penalty has a significant impact on fuel costs when looked at on a yearly basis for a fleet of aircraft.

4.2.3 AIRCRAFT OPERATING WEIGHT

The operating empty weight of an aircraft is defined as the manufacturer’s weight empty plus the operator’s items. The latter include the flight and cabin crew and their baggage, unusable fuel, engine oil, emergency equipment, toilet chemicals and fluids, galley structure, catering equipment, seats, documents, etc.

The OEW of new aircraft, even in the same fleet, can vary significantly, due to specification changes, build differences and normal scatter. Also aircraft generally get heavier all through their operational life. This is due to repair schemes, service bulletins, equipment upgrades, dirt, rubbish and moisture accumulation and unnecessary equipment and supplies.

This variation in weight requires regular monitoring for flight planning purposes. In general most weight growth is inevitable and it cannot be controlled at the operational level. However the airline has to be sensitive to these problems and efforts have to be made in order to avoid excess weight, such as dirt, rubbish and unnecessary equipment and supplies. It should be noted that 100kg of excess weight requires an additional 5000kg of fuel per year per aircraft.

4.2.4 PAYLOAD

The most important part of the take-off weight from an airlines point of view is the payload (passengers and freight). Generally the weight of passengers, carry-on baggage and checked bags are defined in the operating rules by the authorities such as the JAA or the FAA. Most operators use standard weights although other values may be used if they can be statistically demonstrated through surveys. In general there is not much an operator can do to change the situation. However they should be aware of the rules and their validity. If the weights do not seem appropriate then an operator should consider conducting a survey.

As each freight consignment is weighed, the only influence it can have on fuel economy is its location and hence the aircraft CG.

4.2.5 EMBARKED FUEL

Fuel is loaded onto the aircraft to be used as follows:

1. Start-up Fuel
2. Taxi Fuel
3. Trip Fuel
4. Reserve Fuel
5. Fuel for Transportation
6. APU Fuel

In order to avoid unnecessary fuel weight, the flight must be planned very precisely to calculate the exact fuel quantity to be embarked. Flight planning should be based on aircraft performance monitoring by taking into account performance factors derived from specific range variations. In addition the planning should be based on the appropriate optimized techniques using the best achievable routing and flight levels.

More detailed information on this subject is given later in this brochure.

4.3 FLIGHT PLANNING

The fundamental requirement for achieving fuel economy and reduction of operating costs is a quality Flight Planning System.

A good flight planning system will produce an **optimized route**, in terms of track, speeds and altitudes, which meets the operator's economic criteria. This track and vertical profile must be normally achievable in operation, given the constraints of ATC, climb rates, descent rates, etc.

Climb, cruise and descent **techniques** and cruise **flight levels** should be optimized in accordance with the operator's criteria, for both the sector and the diversion. This is covered in much more detail in this brochure.

It will be based on **good quality data** (temperature, wind, aircraft weight, payload, fuel uplift, etc)

It will be use the **correct aircraft performance** and will include an individual aircraft performance factors derived from an ongoing aircraft performance monitoring (APM) program (see "Getting to Grips with Aircraft Performance Monitoring").

Having established the climb, cruise and descent techniques, it should be verified from time to time that the aircrews are using these techniques

The fuel **reserves** will be based on a policy that aims at obtaining the minimum values required within the regulations.

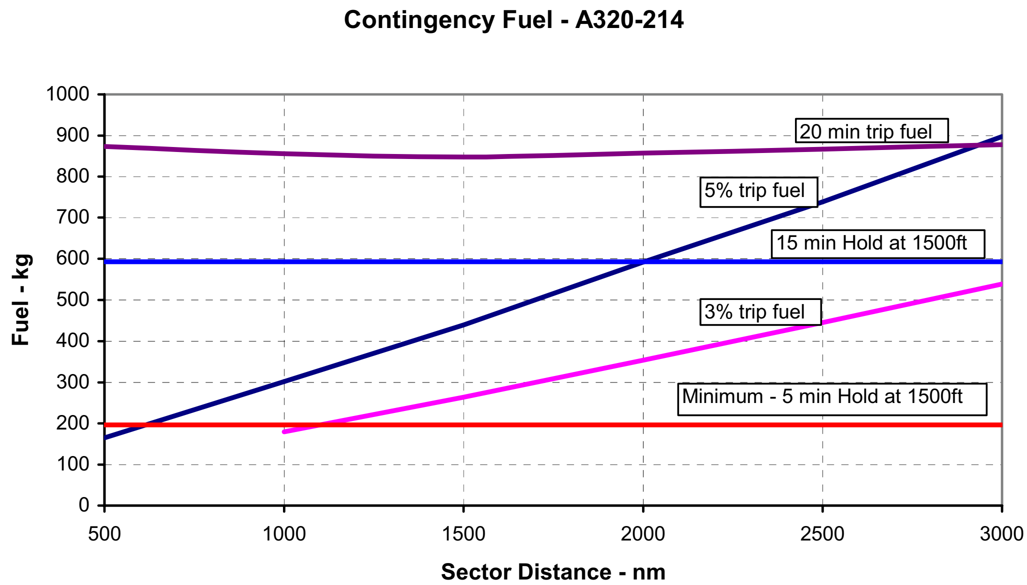
Within JAR OPS, there are several definitions of **Contingency** fuel, depending on diversion airfields, fuel consumption monitoring, etc. Full details can be found in "Getting to Grips with Aircraft Performance", but briefly the fuel is the greater of two quantities:

1. <u>5 minutes hold</u> fuel at 1500 feet above destination at ISA

2. One of the following quantities:
   <u>5% of trip</u> fuel,
   <u>3% of trip fuel</u> with an available en route alternate airport
   <u>15 minutes hold</u> fuel at 1500 feet above the destination at ISA
   <u>20 minutes trip</u> fuel**,** based upon trip fuel consumption.

The last 3 options require airworthiness approval and the last 2 options require fuel consumption monitoring with fuel based on results. What we can conclude is that depending on the flight distance, there is a lowest contingency fuel.

The following graphs show the different contingency fuel quantities for different distances for an A320.



The graphs for other members of the A320 family are similar and indicate that below about 500nm, the contingency fuel is set by the minimum 5-minute hold value. Above about 1000nm, contingency fuel can be reduced to 3% of trip fuel if there is an en-route alternate available. If not, reductions can be made above about 2000nm by using the 15-minute destination hold option, which always requires less fuel than the 20 minute trip fuel option.

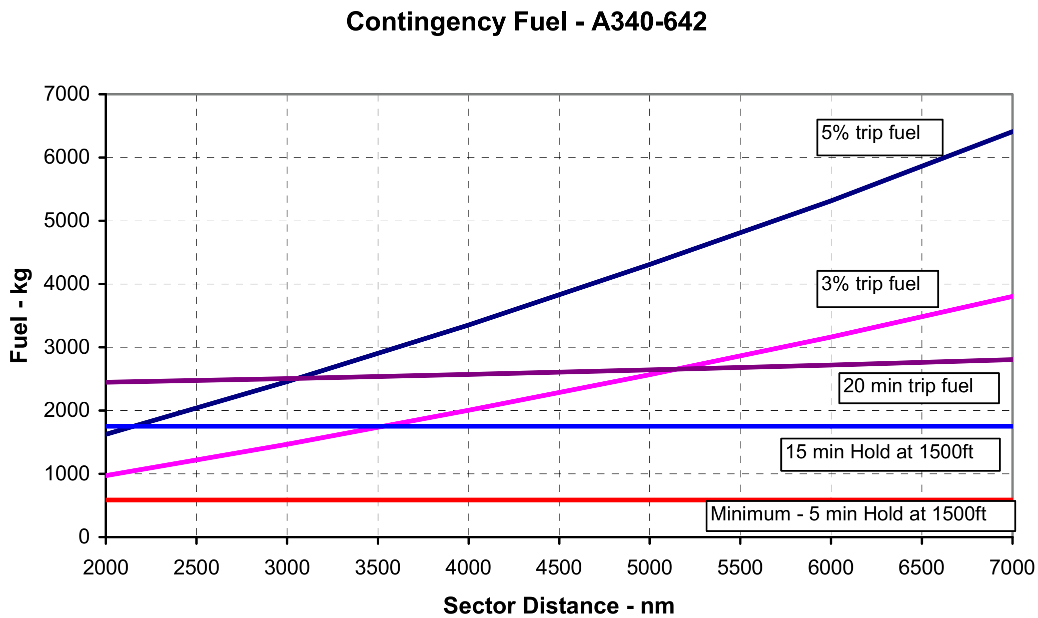
The graphs for the other aircraft show different characteristics because of their longer-range capability.

The A340-600 picture, on the following page, indicates that with no en-route alternate the 15-minute destination hold requirement enables the contingency fuel to be reduced above 2150nm. An en-route alternate will give more benefit until 3500nm, beyond which the 15-minute destination hold minimises the contingency fuel requirement. The A340-500 is similar.

The A300, A310, A330 and other A340's have slightly different critical distances as follows:

5% trip fuel/15-minute hold	1700 to 1900nm.
3% trip fuel/15-minute hold	2800 to 3200nm

However these will also vary with weight, winds, temperature, etc so the limiting reserve should always be checked. Each aircraft type will show critical sector distances beyond which a change in contingency policy will yield benefits.



One further method of reducing the contingency fuel is by using a Decision Point or **Redispatch** Procedure. This involves the selection of a decision point where the aircraft can either continue to the destination as the remaining fuel is sufficient, or it can reach a suitable proximate diversion airport. More details are given in "Getting to Grips with Aircraft Performance".

To minimize the **alternate** fuel, the alternate airports should be chosen as near as possible to the destination.

Both the JAA and FAA do not require the alternate fuel reserve in certain cases, depending on meteorological conditions and the suitability of the airport. More details are given in "Getting to Grips with Aircraft Performance".

Another part of the reserves is the **extra fuel**, which is at the Captain's discretion.

There are many reasons why this extra fuel is necessary. It could be due to uncertain weather conditions or availability of alternate and destination airfields, leading to a probability of re-routing. However it is often due to lack of confidence in the flight planning and the natural desire to increase reserves.

This is the one area where a significant impact can be made through accurate flight planning. With this in place, the aircrew will see that the flight plans fuel burns are being achieved in practice. They will realize that the planned reserves are adequate and that there is no need for more.

4.4 TAXIING

Good estimate of taxi times are required. Actual times need to be monitored and standard estimates changed as necessary. Jet engine performance is optimised for flight conditions, but all aircraft spend considerable time on the ground taxiing from the terminal out to the runway and back. This time has increased due to airport congestion, and increased airport size. This all leads to a waste of precious time and fuel.

Only using one engine for taxiing twin-engine aircraft, or two engines for four-engine aircraft can give benefits in fuel burn. Such procedures need to be considered carefully, and operators have to define their field of application.

Airbus provides standard procedures in the Flight Crew Operating Manual (FCOM) for such operations. The following factors regarding one or two engine out taxi should be considered carefully prior to its incorporation in the operators standard operating procedures:

1. This procedure is not recommended for high gross weights
2. This procedure is not recommended for uphill slopes or slippery runways
3. No fire protection from ground staff is available when starting engine (s) away from the ramp
4. Reduced redundancy increases the risk of loss of braking capability and nose wheel steering.
5. FCOM procedures require not less than a defined time (from 2 to 5 minutes depending on the engine) to start the other engine(s) before take off. On engines with a high bypass ratio, warm-up time prior to applying maximum take off thrust has a significant effect on engine life.
6. Mechanical problems can occur during start up of the other engine(s), requiring a gate return for maintenance and delaying departure time.
7. FCOM procedures require APU start before shutting down the engine after landing, to avoid an electrical transient.
8. FCOM procedures require not less than a defined time before shutting down the other engine(s) after landing. On engines with a high bypass ratio, the cool-down time after reverse operation, prior to shut down has a significant effect on engine life.
9. If an operator decides to use one or two engine out taxi, then FCOM recommendations about which engine(s) to use should be followed.

As engine-out taxi requires more thrust per engine to taxi and maneuver, caution must be exercised to avoid excessive jet blast and FOD. More thrust is necessary for breakaways and 180 degrees turns.

On twin-engine aircraft slow and/or tight taxi turns in the direction of the operating engine may not be possible at high gross weight.

Single engine taxi may also be considered at low weights to avoid excessive use of the brakes to control the acceleration tendency with all engines. This brake use would be detrimental to carbon brake life.

The following table gives an indication of the advantages of engine out taxi for 8 of the 12 minutes total taxi time, leaving 4 minutes warm up time.

Fuel savings with Engine out taxi

Aircraft types	12 minutes taxi (all engines)	12 minutes taxi (8 with engine out)	Engine Out taxi savings
A300-600	300kg	200kg	100kg
A310	240kg	160kg	80kg
A318	120kg	80kg	40kg
A319	120kg	80kg	40kg
A320	138kg	92kg	46kg
A321	162kg	108kg	54kg
A330	300kg	200kg	100kg
A340-200/300	300kg	200kg	100kg
A340-500/600	420kg	280kg	140kg

For engine out or all engines taxi, the use of a slow taxi speed costs fuel and time. A burst of power should be used to get the aircraft to taxi speed, then the power should be reduced to idle. However 30kt should not be exceeded.

4.5 FUEL FOR TRANSPORTATION

The normal message regarding fuel burn is that it is more economical to carry the minimum amount required for the sector. However there are occasions when it is economic to carry more fuel. This is when the price of fuel at the destination airfield is significantly higher than the price at the departure airfield.

However, since the extra fuel on board leads to an increase in fuel consumption the breakeven point must be carefully determined.

K is the **transport coefficient**:

$$\boxed{K = \frac{\Delta TOW}{\Delta LW}}$$

The addition of one tonne to the landing weight, means an addition of K tonnes to the take-off weight.

For example, if K=1.3 and 1300 kg fuel is added at the departure, 1000 kg of this fuel amount will remain at the destination. So carrying one tonne of fuel costs 300 kg fuel more.

The extra-cost of the loaded fuel at departure is

Fuel weight x departure fuel price $(\Delta TOW \times P_d = \Delta LW \times K \times P_d)$

The cost saving of the transported fuel is

Transported fuel x arrival price $(\Delta LW \times P_a)$

The cost due to a possible increase in flight time is

Flight time increase x cost per hour $(\Delta T \times C_h)$

It is profitable to carry extra fuel if the cost saving exceeds the extra fuel loaded cost plus the extra time cost.

$$(\Delta LW \times P_a) > (\Delta LW \times K \times P_d) + (\Delta T \times C_h)$$

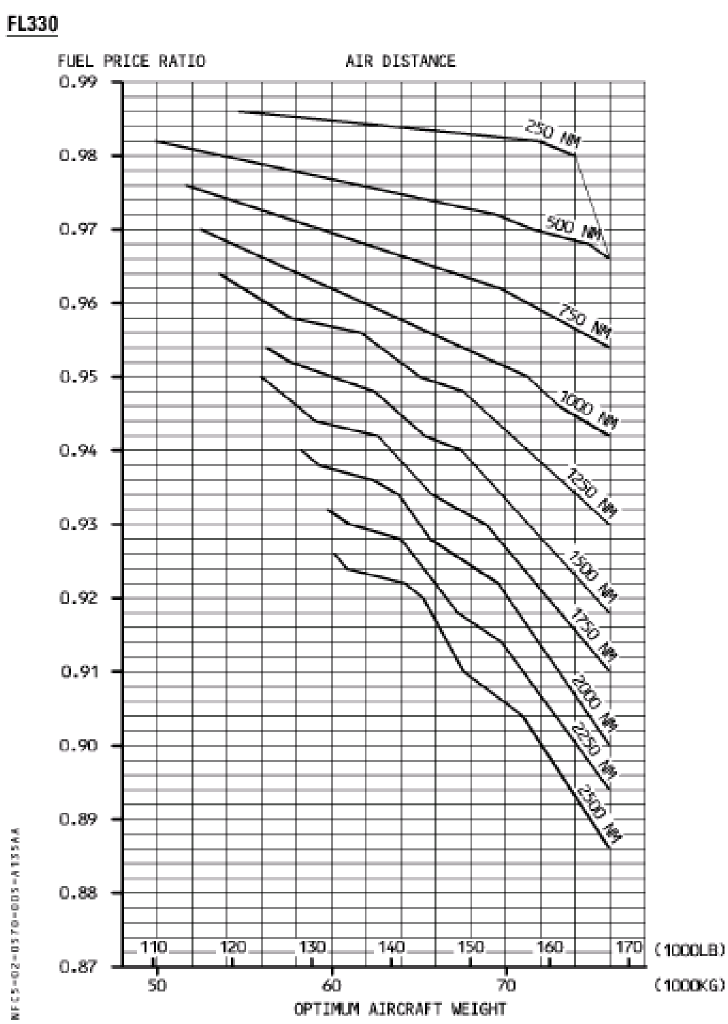
That is to say:

$$\Delta LW \,(P_a - K \times P_d) - (\Delta T \times C_h) \; > \; 0$$

Therefore, if $\Delta T=0$, it is profitable to carry extra fuel if the arrival fuel price to departure fuel price ratio is higher than the transport coefficient K.

$$\frac{P_a}{P_d} > K$$

Thus carrying extra fuel may be of value when a fuel price differential exists between two airports. Graphs in the FCOM assist in determining the optimum fuel quantity to be carried as a function of initial take-off weight (without additional fuel), stage length, cruise flight level and fuel price ratio. The following graph is an example for an A320.



However the needs for accurate fuel planning is necessary to avoid arriving at the destination airport overweight. This could result in the economic benefit being eroded or negated due to extra hold time or circuits.

4.6 AUXILIARY POWER UNIT

The Auxiliary Power Unit (A.P.U.) is a self-contained unit which makes the aircraft independent of external pneumatic and electrical power supply and environmental conditioning.

A.P.U. fuel consumption obviously represents very little in comparison with the amount of fuel for the whole aircraft mission. Nevertheless, operators have to be aware that adopting specific procedures on ramp operations can help save fuel and money.

On the ground, A.P.U. fuel consumption depends on the A.P.U. type load and the ambient conditions. The minimum is when the APU is in the RTL(ready to load) condition. As additional loads, such as Electrical Loads(EL) and Environmental Conditioning System (ECS), are connected, the fuel consumption increases as shown in the following table (ISA, SL conditions).

Aircraft Type	APU Model	RTL	RTL Max EL	Min ECS Max EL	Max ECS Max EL
A320 family	36-300	70 kg/hr	85 kg/hr	105 kg/hr	125 kg/hr
A320 Family	131-9A	75 kg/hr	95 kg/hr	115 kg/hr	125 kg/hr
A330, A340	331-350	120 kg/hr	140 kg/hr	175 kg/hr	210 kg/hr
A340-500/600	331-600	160 kg/hr	180 kg/hr	225 kg/hr	290 kg/hr

A.P.U. specific procedures to save fuel have to be defined by the operators. One extra minute of A.P.U. operation per flight at 180 kg/hr fuel flow, means an additional 3000 kg per year per aircraft. This will also result in increased maintenance costs.

They have to choose between using ground equipment (Ground Power Unit, Ground Climatisation Unit, Air Start Unit) and the A.P.U. This choice depends on several parameters and each operator needs to determine the benefits at each airport and at each turnaround.

Such parameters can include length of turnaround, ambient conditions, cost of ground connections, time delay to get connected, suitability and quality of ground equipment, passenger load, local noise restrictions, etc.

For a **long turnaround** or **night stop** the G.P.U. is the best choice as time considerations are not prevailing. It saves both fuel and A.P.U. life. So operators are advised to use ground equipment if of a good quality, and to try to conclude agreements with airport suppliers to get preferential prices.

However, for a **short turnaround** (45 minutes on average), the use of A.P.U. may be preferable to limit A.P.U. start cycles and improve reliability, even if it is not fully used during the turnaround. It is better to operate with A.P.U. at RTL than to shut it down and perform a new start cycle soon after shut down. Lack of suitable ground power may also require the use of APU. The use of APU may also be preferable to avoid excessive hook up charges or to reduce turnaround time.

Some airport regulations restrict the use of the APU to a defined time prior to departure time and after the arrival.

For **extremely short turnarounds**, complete engine shut down would have a cyclic cost impact, and therefore the turnaround could be made without APU. However a main engine can sometimes not meet the ECS demand in high load conditions (hot days).

The disconnection of ground equipment supplies and the start of A.P.U. must be coordinated with A.T.C. pushback/slot requirements. A **one-minute anticipation** in each A.P.U. start will lead to a significant amount of fuel saving during a year (2000 to 4000 kg depending on A.P.U. types).

Engine start up should also, if possible, be carefully planned in conjunction with A.T.C. If pushback is delayed, it is preferable to wait and use A.P.U. for air conditioning and electrical requirements. Engine start time is critical, and the engines should not be started until ready to go.

The following table assuming typical engine fuel flows, shows extra fuel consumption by using one engine instead of the A.P.U. for 1 minute, assuming maximum electrical load and minimum ECS:

Extra fuel when using Engine instead of APU

Aircraft Type	A.P.U. type	Engine FF kg/hr/eng	APU FF kg/hr	Extra Fuel for 1 minute
A300 GE	331-250	520	150kg	6kg
A310 GE	331-250	520	150kg	6kg
A320 family CFM	36-300	300	105kg	3kg
A330 GE	331-350	520	175kg	6kg
A330 RR	331-350	720	175kg	9kg
A340 CFM	331-350	300	175kg	2kg
A340 RR	331-600	480	275kg	4kg

In overall economic terms, the benefits of APU operation are not just confined to fuel usage. The hourly maintenance costs of an APU are cheaper than the aircraft powerplant, so reducing ground running time on the engines can significantly reduce the operating costs.

4.7 AERODYNAMIC DETERIORATION

Some of the most severe penalties in terms of fuel consumption are caused by increased drag resulting from poor airframe condition. Normal aerodynamic deterioration of an aircraft over a period of time can include the incomplete retraction of moving surfaces, damaged seals on control surfaces, skin roughness and deformation due to bird strikes or damage caused by ground vehicles, chipped paint, mismatched doors and excessive gaps. Each deterioration incurs a drag increase, and this increased drag is accompanied by increased fuel consumption.

This subject is covered fully in the brochure "Getting Hands-On Experience with Aerodynamic Deterioration".

The following table gives the highest deterioration effect in each category for the three aircraft families as increased sector fuel consumption in Kg, based on typical utilization figures.

Category	Condition	A300/310	A320 Family	A330/340
Misrigging	Slat 15mm	90	60	270
Absence of Seals	Flap (chordwise)	30	14	90
Missing Part (CDL)	Access Door	50	13	150
Mismatched Surface	Fwd Cargo Door 10mm step for 1m	20	11	80
Door seal leakage	Fwd Pax Door 5cm	2	1	5
Skin Roughness	1 m^2	21	13	105
Skin Dents	Single	2	1	2
Butt joint gaps	Unfilled	0.2	0.1	0.6
Butt Joint Gaps	Overfilled	3	2	7
External Patches	1 m^2 3mm high	6	3	16
Paint Peeling	1 m^2 leading edge slat	12	8	57
	Sector Distance	2000nm	1000nm	4000/6000nm

5. IN FLIGHT PROCEDURES

When an aircraft arrives at the end of the runway for take-off, it is the flying techniques (speed, altitude, configuration, etc) that have the biggest influence on fuel economy. Disciplined flight crews adhering to a flight plan based on the operator's priorities can save much fuel and/or costs.

This part intends to give recommendations to flight crews on the means to save fuel during the flight. It reviews the different phases of the flight, that is to say:

- Take-off and Initial Climb
- Climb
- Cruise
- Descent
- Holding
- Approach

5.1 TAKE-OFF AND INITIAL CLIMB

5.1.1 INTRODUCTION

There are many variations in take-off technique that can directly affect the fuel burn. In general the effects are very dependent on the airframe/engine combination as well as aircraft weight, airfield altitude and temperature. The following fuel effects are representative values.

5.1.2 BLEEDS

For take-off, full bleeds can be used or one can consider selecting packs off or APU bleed on to improve take-off performance. Selecting packs off **without APU** will also improve fuel burn. The normal procedure would then be to select pack 1 on after climb thrust is selected and pack 2 on after flap retraction. This has the effect of reducing fuel burn by 2-3 kg on an A320 increasing to 5-10 kg on an A340-500/600.

With APU bleed the engine fuel burn will be decreased by the same amount. However with APU used from pushback with 12minutes taxi, the additional APU fuel burn is 30kg for an A320 and 60-70kg for an A340.

In economic terms, the APU fuel and maintenance cost is largely offset due to decreased engine maintenance costs bleeds off (higher flex temp).

5.1.3 CONFIGURATION

This effect is very dependent on the variables mentioned in the introduction, plus the choice of VR and V2. However the trend is always the same , with high flap/slat configurations (more extended) using more fuel than the lowest setting. Typical penalties/takeoff of higher flap settings compared with the low flap settings Conf 1+F are shown below (note that for the A300/A310 Conf 1+F, Conf 2 and Conf 3 corresponds to the Flap 0,15 and 20 configuration respectively).

Aircraft	Conf 2	Conf 3
A300/A310	1- 5kg	15kg
A320	3-5kg	8-13kg
A330	12kg	24kg
A340	30kg	50kg

These figures assume Full take-off thrust. The advantage of Conf 1+F increase with reduced power take-offs.

5.1.4 SPEEDS

During a non limiting full power take-off, the use of the higher speeds appropriate to flex thrust instead of optimized speeds appropriate to the actual temperature can reduce the fuel burn by up to 8kg.

5.1.5 FLEX THRUST

Compared to a full thrust take-off, flex thrust will generally increase fuel burn. The increased time at low level offsets the slight reduction in fuel flow induced by the lower thrust. Typical increases are as follows:

Aircraft	Conf 1+F	Conf 2	Conf 3
A300/A310	10kg	10kg	10kg
A320	1kg	5kg	5kg
A330	0	0	0
A340	5kg	20kg	25kg

5.1.6 NOISE FLIGHT PATHS

The effect of an ICAO type A noise flight path, with climb thrust selected at 800ft and clean up delayed until 3000ft is generally to increase fuel burn compared to the standard take-off with power reduced at 1500ft. The actual distance to a fixed height, say 5000ft, varies very little with configuration. The main effect is the different altitude – speed history experienced by the engines. Typical values are as follows:

Aircraft	Conf 1+F	Conf 2	Conf 3
A320	-4kg	+5kg	+2kg
A330	+100kg	+100kg	+115kg
A340	+90kg	+130kg	+125kg

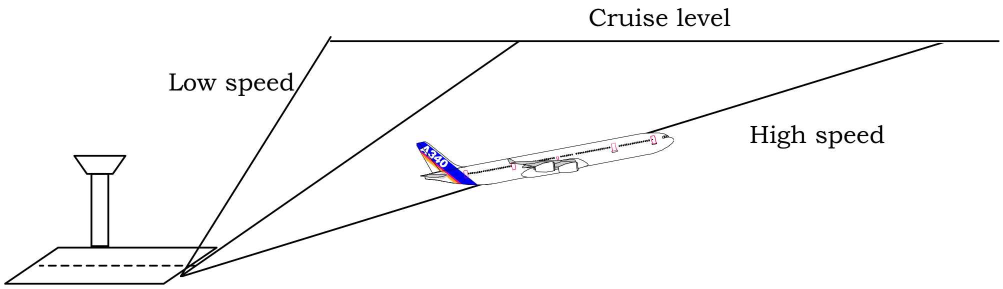
5.1.7 COURSE REVERSAL

In the event that a course reversal is required after take-off, then much distance can be saved using a lower initial climb speed. Suppose ATC require an aircraft to maintain runway heading to 6000ft. A lower climb speed will achieve this altitude earlier and thus reduce the ground distance and fuel burnt.

5.2 CLIMB

5.2.1 INTRODUCTION

Depending on speed laws, the climb profiles change. The higher the speed, the lower the climb path, the longer the climb distance.



Climb profiles

Climbs are normally performed in three phases on a constant IAS/Mach climb speed schedule at max climb thrust, as follows:

- 250 KT indicated air speed (IAS) is maintained until flight level 100, then the aircraft accelerates to the chosen indicated air speed (e.g. "300kts);
- constant indicated air speed is maintained until the crossover altitude;
- constant Mach number is maintained until top of climb;

The crossover altitude is the altitude where we switch from constant IAS climb to the constant Mach number climb. It only depends on the chosen IAS and Mach number, and does not depend on ISA variation.

During climb, at constant IAS, the true air speed (TAS) and the Mach number increase. Then, during climb at constant Mach number, the TAS and the IAS decrease until the tropopause.

To correctly evaluate the effects of climb techniques, climb and cruise flight must be viewed in relation to each other. A short climb distance for example extends the cruise distance; a low climb speed requires more acceleration to cruise speed at an unfavourable high altitude. One has therefore to consider sectors that cover acceleration to climb speed, climb, acceleration to cruise speed and a small portion of the cruise to the same distance.

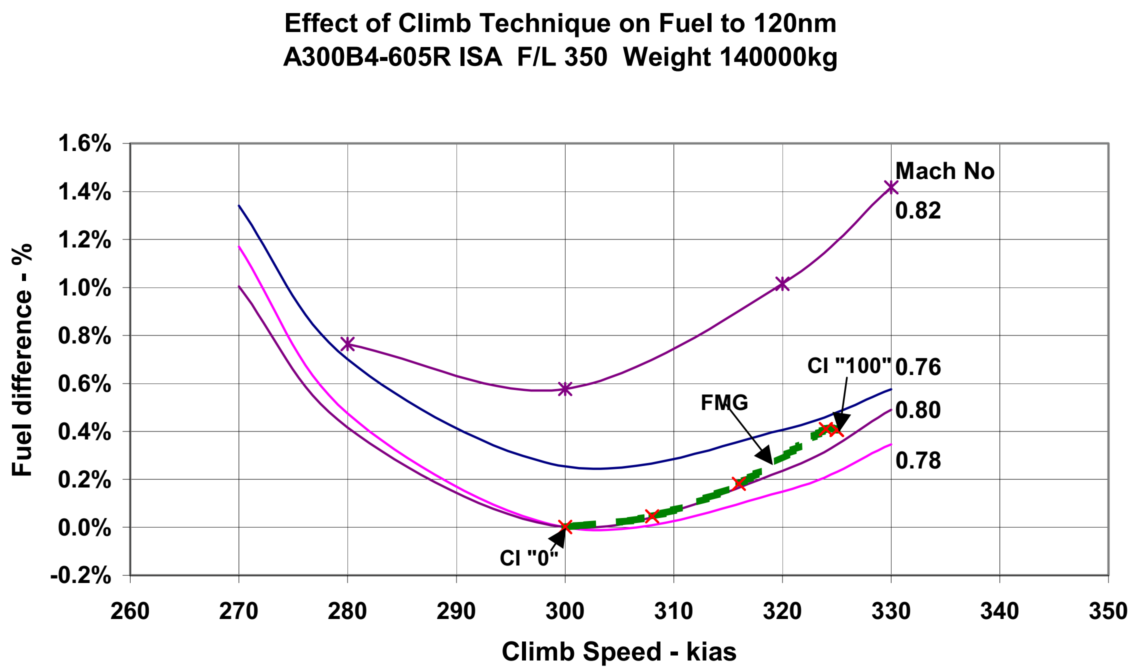
5.2.2 THE EFFECT OF CLIMB TECHNIQUE ON FUEL BURN

This evaluation has been made for all Airbus types, based on a climb to 35000ft, acceleration and cruise to a fixed distance. The assumed cruise speed was 0.78 for the A320 family and 0.8 for the rest.

The reference climb technique is the standard technique given in each FCOM, and is summarized below:

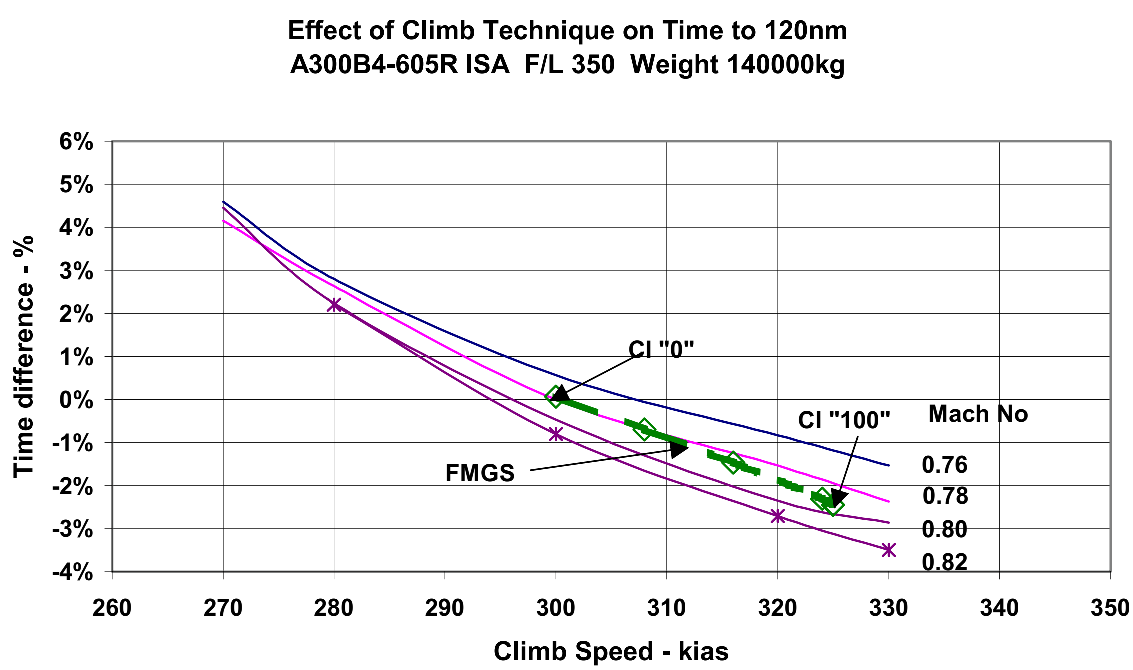
Aircraft types	Speed law
A300-600	250kts/300kts/M0.78
A310 (GE)	250kts/300kts/M0.79
A310 (PW)	250kts/300kts/M0.80
A318/A319/A320/A321	250kts/300kts/M0.78
A330	250kts/300kts/M0.80
A340-200/300	250kts/300kts/M0.78
A340-500/600	250kts/320kts/M0.82

The following chart shows the variation of fuel burn with climb technique over a given climb + cruise distance.



This shows that there is an optimum climb speed and max climb Mach number that produces the lowest fuel burn. This happens to be the standard technique (300kt/0.78). Climbing at 320kt/0.82 will burn 1% more fuel.

However the following chart shows that this is obtained at the **expense of time.**



This time difference plot has the same characteristics for all Airbus aircraft, with the best time being obtained at the highest climb speed and max climb Mach number. Note that although a slow climb speed gets the aircraft to cruise altitude earlier, this requires more acceleration to cruise speed and more cruise to a given distance, making it slower overall.

The fuel difference plot characteristics vary with aircraft type. The A310, A321 and A330 show similar characteristics to the A300 with a best fuel climb speed of about 290 to 300 knots.

The A318, A319 and A320 show better fuel burn at the lower speed range (260 to 280 knots)

The A340 shows better fuel burn at the higher speed range (310-330 knots).

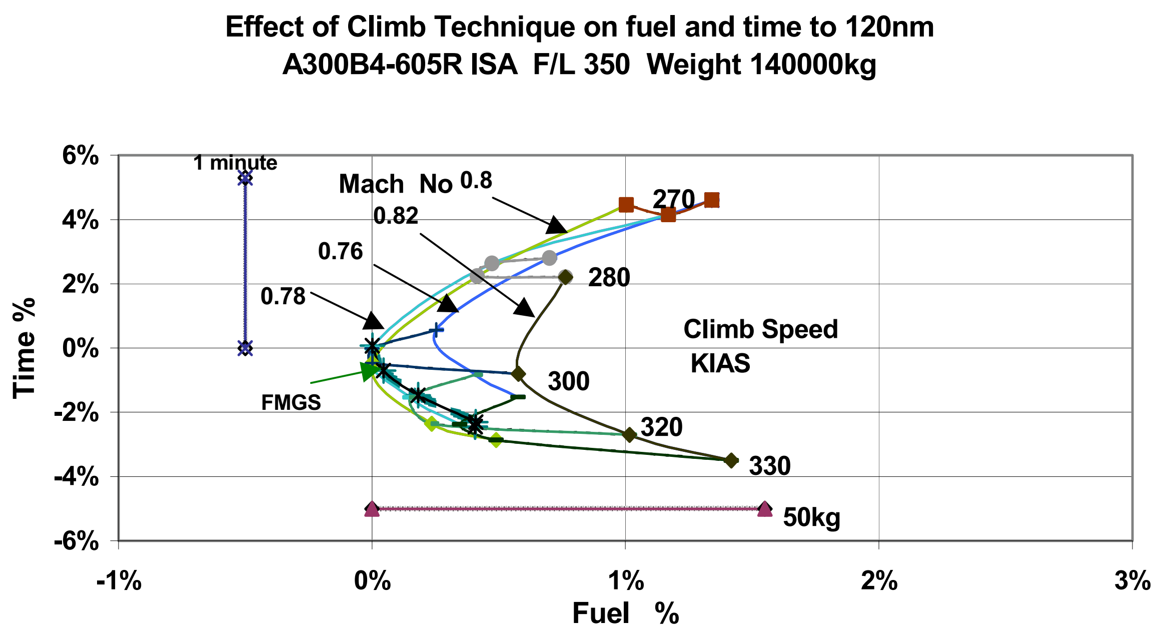
The A310 and A340 are similar to the A300 in showing minimum fuel at a max climb Mach number of 0.78. In fact 0.8 is better for the A340-500/600.

However the A320 family and A330 benefit from the lower Mach No of 0.76.

Thus the A320 family benefits from low climb speeds and the A340 from high climb speeds. This difference arises from the different behavior during climb of twin-engine and four-engine aircraft. Indeed, twin-engine aircraft have a higher thrust than four engine aircraft, as they must satisfy some take-off climb requirements with only one engine operative, compared with 3 engines operative on the quads. This enables them to have a higher rate of climb than four engine aircraft and reach cruise flight levels quicker.

5.2.3 CORRELATION OF FUEL BURN & TIME WITH CLIMB TECHNIQUE

The following chart shows the differences in fuel and time to climb and cruise to a fixed distance with varying climb speed and max climb Mach number relative to the standard technique.

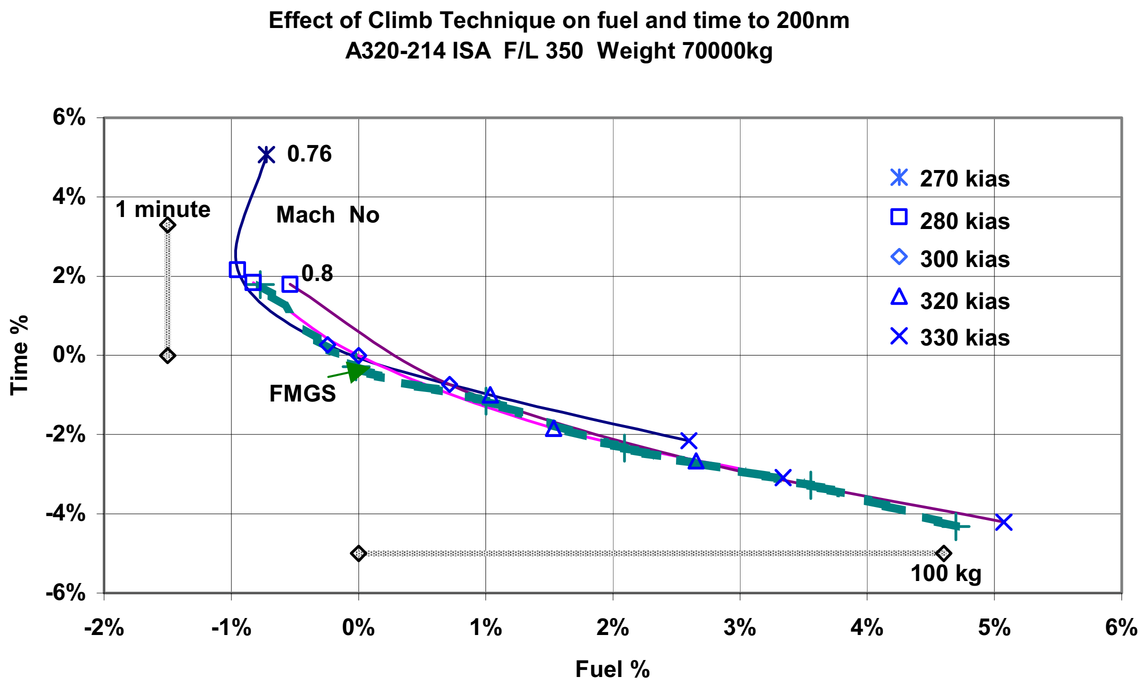


This chart shows that the fastest technique (330/0.82) uses the least time (-3.2%) and the most fuel (+1.5%) whereas the slowest technique (270/0.76) uses the most time (+4.5%) and nearly the most fuel (+1.4%). The least fuel is obtained using a 300/0.78 climb technique. Variation of climb technique can cause a total variation of 1.5% and climb time by 8% for this aircraft.

Also plotted on the charts are lines representing the speeds selected by the FMGS for various cost indices (CI). The left hand point of each line represents a CI of zero (fuel cost priority) and the right hand point represents a CI of 100 (flight time priority). It should be noted how the FMGS line approximates to the lower boundary of the time - fuel difference plot.

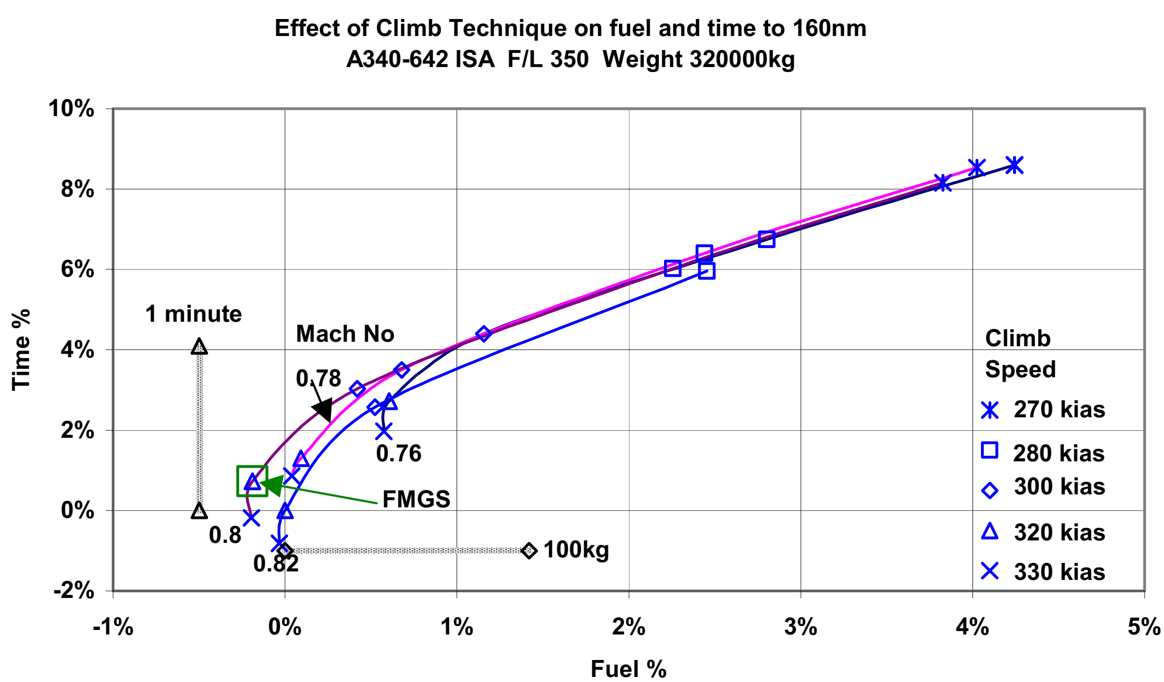
The chart on the following page is for the A320 and shows completely different characteristics.

The different mach numbers all coalesce together and the FMGS line forms the



common boundary. Climb speed increases from the left to the right. Least fuel is obtained using a 0.76/280 technique. Mach No has little influence, but increasing speed from 280 to 330kias decreases time by 6% and increases fuel by 6%.

Completely different characteristics are also shown in the next chart (A340-642).



This shows a common technique is good for both fuel burn and time. The optimum is 320/0.80. There is little Mach No effect, but reducing the speed to 270 kias will increase fuel by 4% and time by 8%. Because the optimum technique is good for both fuel and time, there is a single FMGS point for all cost indeces.

Earlier versions of the A340 showed that some marginal time benefit could be gained by climbing faster. However this would have affected the flight levels achieved. Consequently there is no variation of FMGS climb speed with cost index for all the A340 family.

Appendix A presents some examples of time - fuel charts for other Airbus aircraft.

5.2.4 CLIMB TECHNIQUE COMPARISON TABLES

The following tables show, for various Airbus aircraft, the climb time and fuel variations for a fixed distance, to FL 350, relative to a 300kias reference speed.

Effect of Climb Speed on Fuel

Aircraft	Climb	ΔFuel – kg				
	Mach No.	270KT	280 KT	300 KT	320 KT	330 KT
A300	0.78	+40	+15	0	+5	+10
A310	0.79		+5	0	+5	+15
A318/A319/A320	0.78		-15	0	+30	+70
A321	0.78		-10	0	+25	+60
A330	0.80	+15	+5	0	+20	+35
A340–200	0.78	+45	+20	0	+10	+25
A340-300	0.78	+105	+50	0	-5	+20
A340-500/600	0.82		+135	0	-5	-10

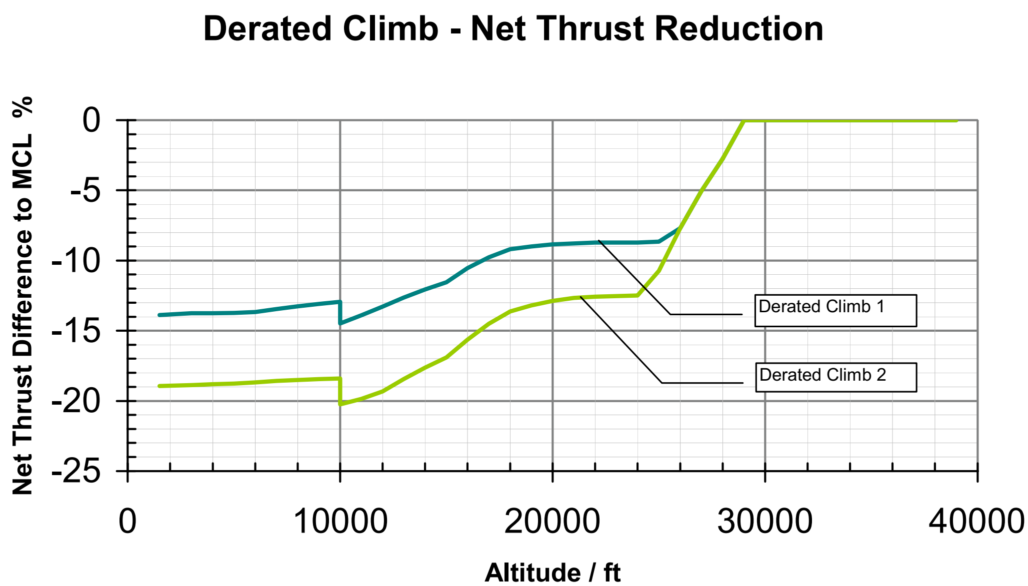
Effect of Climb Speed on Time

Aircraft	Climb	ΔTime – minutes				
	Mach No.	270KT	280 KT	300 KT	320 KT	330 KT
A300	0.78	+0.8	+0.5	0	-0.3	-0.4
A310	0.79		+0.5	0	-0.5	-0.6
A318/A319/A320	0.78		+0.5	0	-0.4	-0.8
A321	0.78		+0.8	0	-0.6	-1.0
A330	0.80	+0.9	+0.6	0	-0.4	-0.7
A340–200	0.78	+1.4	+0.8	0	-0.6	-0.8
A340-300	0.78	+1.5	+0.9	0	-0.6	-1.0
A340-500/600	0.82		+0.8	0	-0.6	-0.8

It can be seen from the tables how the optimum techniques are very dependant on the aircraft type, and that a 10kt climb speed change can have a significant impact.

5.2.5 DERATED CLIMB

In order to reduce engine maintenance costs, there are derated climb options available on the A330 and A340 aircraft. There are two levels of derate, D1 and D2. At a certain altitude the derate is washed out such that at Max Climb rating is achieved generally before 30000ft. The following shows a typical derate thrust variation picture, but this will vary with engine and temperature.



However this derate will result in more fuel and time required to reach the same distance. The effect is dependant on aircraft weight, temperature and cruise flight level. The following table gives some typical penalties in ISA conditions to 35000ft.

Aircraft	Weight (kg)	Derate D1		Derate D2	
		Fuel Increase	Time Increase	Fuel Increase	Time Increase
A330-203	190000	5kg	0.5 min	20kg	0.6 min
A330-223	190000	20kg	0.2 min	40kg	0.5 min
A330-343	190000	20kg	0.2 min	40kg	0.5 min
A340-212	240000	65kg	0.9 min	120kg	1.5 min
A340-313	240000	140kg	0.8 min	225kg	1.4 min
A340-313E	240000	140kg	1.0 min	335kg	1.4 min
A340-642	340000	270kg	0.6 min	445kg	1.0 min

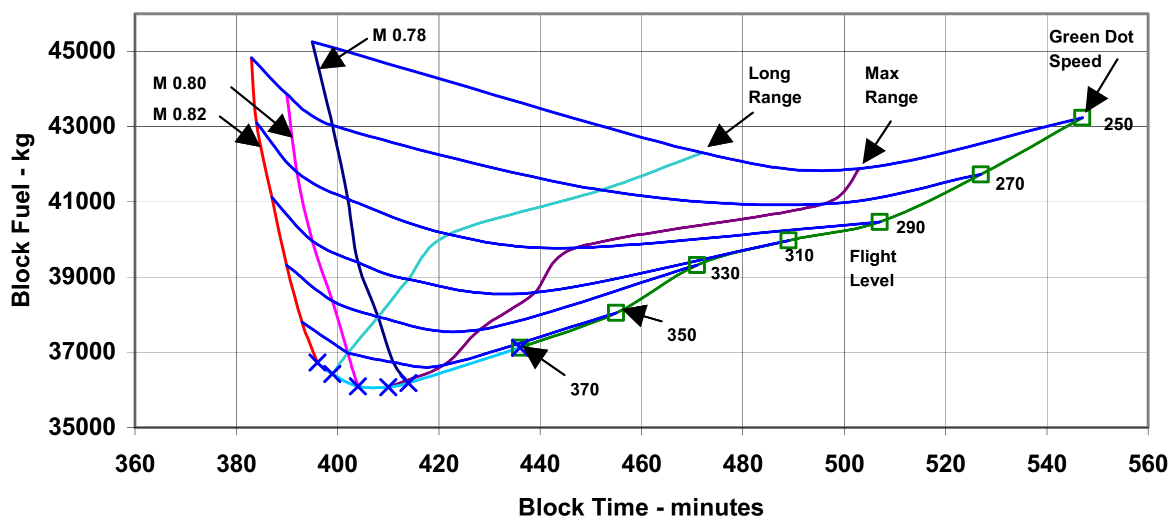
5.3 CRUISE

5.3.1 INTRODUCTION

The cruise phase is the most important phase regarding fuel savings. As it is the longest for long haul aircraft, it is possible to save a lot of fuel. So discipline must be exercised particularly in this phase.

The two variables that most influence cruise fuel consumption are the cruise speed (IAS or Mach Number) and the altitude or flight level. The following shows their influence on a single sector assuming standard climb and descent procedures.

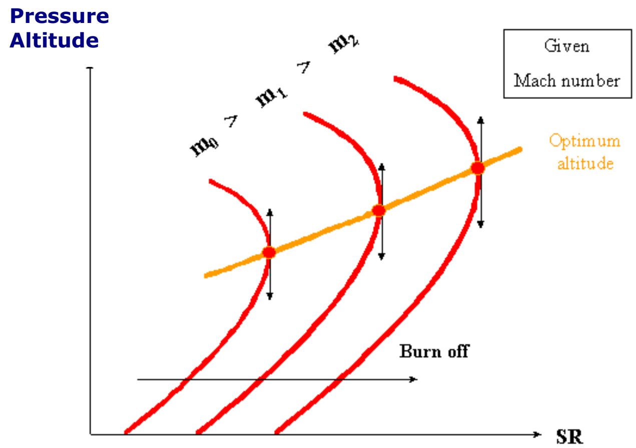
Block Fuel and Time for various Flight Levels and Mach numbers
A330-223 ISA 3000nm Payload 30000kg JAR Reserves



The correct selection of the cruise parameters is therefore fundamental in minimizing fuel or operating cost. This chart shows the normal laws that aircraft consume less fuel when flown slower or when flown higher. However there are limits to these laws. Flying lower than the maximum range speed will increase the block fuel, as will flying higher than an optimum altitude.

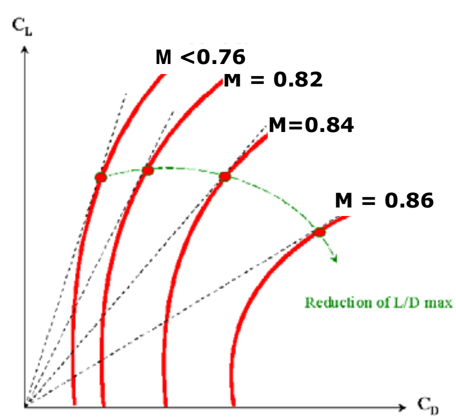
5.3.2 CRUISE ALTITUDE OPTIMISATION

In examining SR changes with the altitude at a constant Mach number, it is apparent that, for each weight, there is an altitude where SR is maximum. This altitude is referred to as "optimum altitude".



Optimum Altitude Determination at Constant Mach Number

When the aircraft flies at the optimum altitude, it is operated at the maximum lift to drag ratio corresponding to the selected Mach number.



High Speed Polar Curve

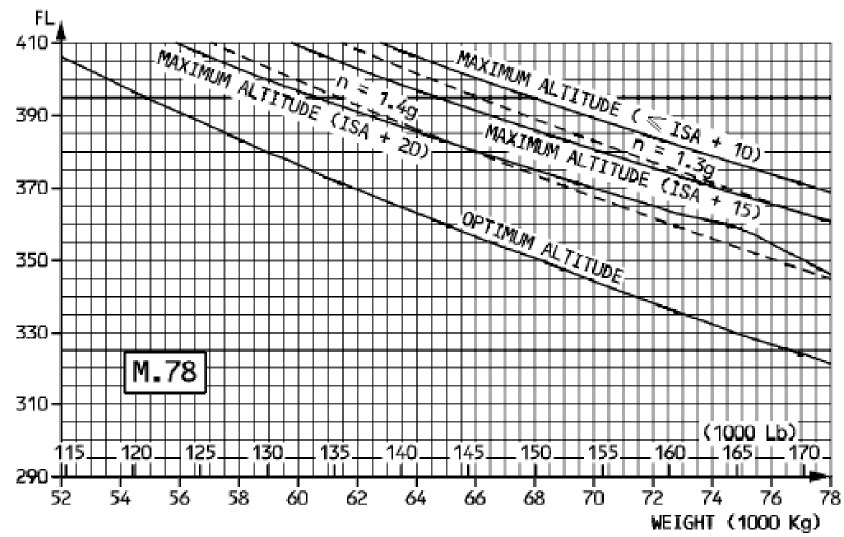
When the aircraft flies at high speed, the polar curve depends on the indicated Mach number, and decreases when Mach increases. So, for each Mach number, there is a different value of $(C_L/C_D)_{max}$, that is lower as the Mach number increases.

When the aircraft is cruising at the optimum altitude for a given Mach, C_L is fixed and corresponds to $(C_L/C_D)_{max}$ of the selected Mach number. As a result, variable elements are weight and outside static pressure (P_s) of the optimum altitude. The formula expressing a cruise at optimum altitude is:

$$\boxed{\frac{\text{Weight}}{P_s} = \text{constant}}$$

In the FCOM Flight Planning Chapters the optimum altitude is shown on the Cruise Level chart for 2 or more speeds. This chart also shows the Maximum Altitudes as limited by performance and buffet. A typical FCOM chart showing the variation of optimum altitude with weight for one speed is shown below.

A318/319/320/321 FLIGHT CREW OPERATING MANUAL	FLIGHT PLANNING CRUISE LEVEL	2.05.20	P 2
		SEQ 205	REV 26



It should be noted that the influence of airspeed on optimum altitude is not very significant in the range of normal cruise speeds.

In order to minimize fuel burn, the aircraft should therefore be flown at the optimum altitude. However this is not always possible. Performance limitations such as rate of climb or available cruise thrust can lead to a maximum altitude below the optimum, as can buffet limitations. At low weights, the optimum altitude may be above the maximum certificated altitude. In addition, Air Traffic Control restrictions can affect the flown flight level.

The following table shows the specific range penalty of not flying at optimum altitude, assuming a cruise Mach No of 0.8. It should be noted that each airframe/engine combination has different values. It should be noted that these are average values and there are slight variations with different weight/optimum altitude combinations.

Specific Range Penalty for not flying at Optimum Altitude

Aircraft	+2000ft	-2000ft	-4000ft	-6000ft
A300B4-605	2.0%	0.9%	3.4%	9.3%
A310-324	1.9%	1.4%	4.4%	9.3%
A318-111	0.7%	1.6%	5.0%	10.0%
A319-132	1.0%	3.0%	7.2%	12.2%
A320-211	**	1.1%	4.7%	9.5%
A320-232	1.4%	2.1%	6.2%	12.0%
A321-112	2.3%	1.4%	4.6%	15.2%
A330-203	1.8%	1.3%	4.2%	8.4%
A330-343	3.0%	1.0%	3.2%	7.2%
A340-212	1.4%	1.5%	4.0%	8.0%
A340-313E	1.5%	1.6%	5.2%	9.5%
A340-642	1.6%	0.6%	2.2%	5.1%

** Above Maximum Altitude

Generally if one flies within 2000ft of optimum altitude, then the specific range is within about 2% of the maximum. However fuel burn-off is an important consideration.

Consider an A340-313E at a weight such that the optimum altitude is 33000ft. If the aircraft flies at FL 310 the SR penalty is 2.1% for the weight considered. However after a fuel burn of 20800kg, during which the aircraft would have traveled 1400nm the optimum altitude increases to 35000ft and the penalty is now 5.2%.

There is also an effect on block time due to the different altitudes. The true air speed increases/decreases 4kts, or just under 1% for each 2000ft lower/higher cruise altitude.

5.3.2.1 CROSS-OVER ALTITUDE VERSUS OPTIMUM ALTITUDE

It has been previously shown that the TAS is the maximum at the crossover altitude. One can wonder whether it is profitable to stay at this altitude, instead of climbing to the first optimum altitude.

Assuming the standard climb laws, the crossover altitude can be derived. The standard speed laws are tabulated in paragraph 5.2.2.

The next table shows the effect of flying at the crossover altitude instead of optimum flight levels. The 1st optimum flight level has been chosen for the short sectors, whereas longer sectors assume step climbs with FL 310, 350 and 390 being available. This assumes ISA conditions and a take-off weight for a typical sector with max passengers and some freight (2500kg for the A320 family and 5000kg for the other aircraft).

Aircraft type	Sector Distance	Cross-over altitude	Optimum Flight Levels	Gained time (min)	Increase in fuel consumption
A300B4-605R	2000nm	29000 ft	310/350	7	1190kg
A310-324	2000nm	30000ft	350/390	3	2160kg
A318-111	1000nm	29000 ft	370	3	740kg
A319-112	1000nm	29000 ft	370	3	650kg
A320-214	1000nm	29000 ft	350	2	580kg
A320-232	1000nm	29000 ft	340	2	440kg
A321-211	1000nm	29000 ft	330	2	350kg
A330-203	4000nm	31000 ft	350/390	9	5040kg
A330-223	4000nm	31000 ft	350/390	9	5780kg
A330-343	4000nm	31000 ft	350/390	10	6380kg
A340-212	6000nm	29000 ft	310/350/390	17	10900kg
A340-313	6000nm	29000 ft	310/350/390	14	8410kg
A340-313E	6000nm	29000 ft	310/350/390	17	9310kg
A340-500/600	6000nm	29000 ft	310/350/390	18	2430kg

This table shows that flying at crossover altitude increases the fuel burn significantly for a relatively small reduction in block time.

5.3.2.2 CRUISE OPTIMISATION WITH STEPPED CLIMB

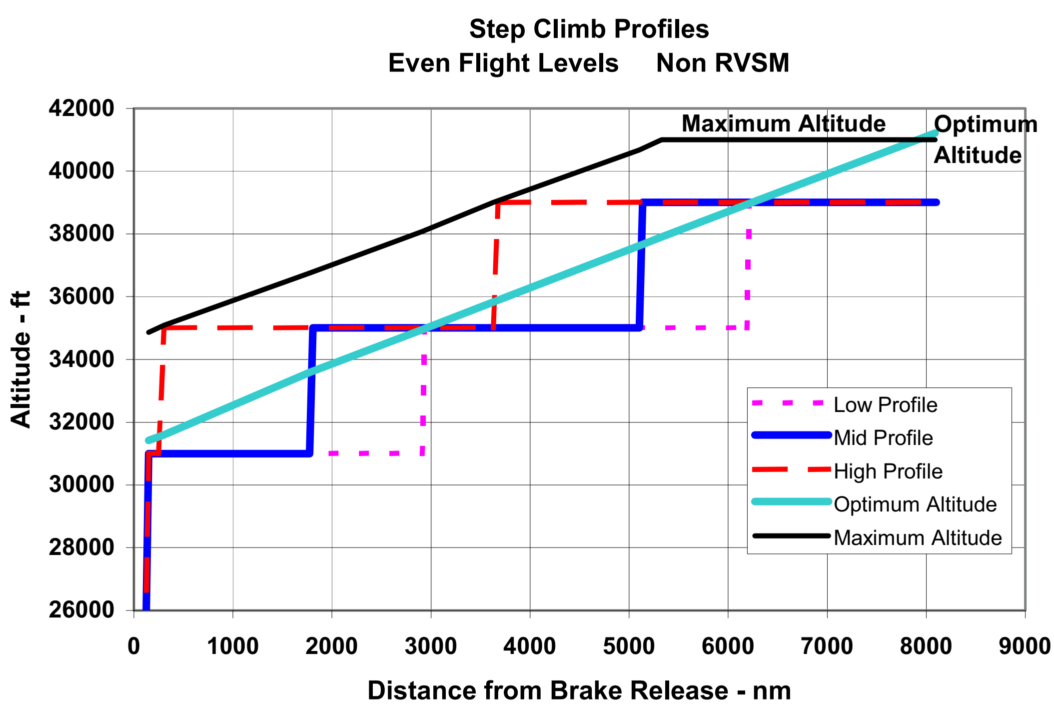
5.3.2.2.1 Introduction

It has been shown that flying at non-optimum altitudes can cause significant fuel penalties, and that the effect of fuel burn is to increase the optimum altitude. The ideal scenario would be to follow the optimum altitude as in the climbing cruise, but A.T.C. constraints, performance and buffet limits do not make this possible. However, by changing the cruise level with step climbs, as the aircraft gets lighter the aircraft will remain as close as possible to the optimum altitude.

5.3.2.2.2 Choice of Profile

Several parameters such as weather conditions, ATC requirements, may influence any decision made by the crew with regard to three fundamental priorities: maneuverability, passenger comfort, and economics.

This pertains to the choice of the cruise flight level that can be made according to the three following climb profiles as shown below for an A340-642:



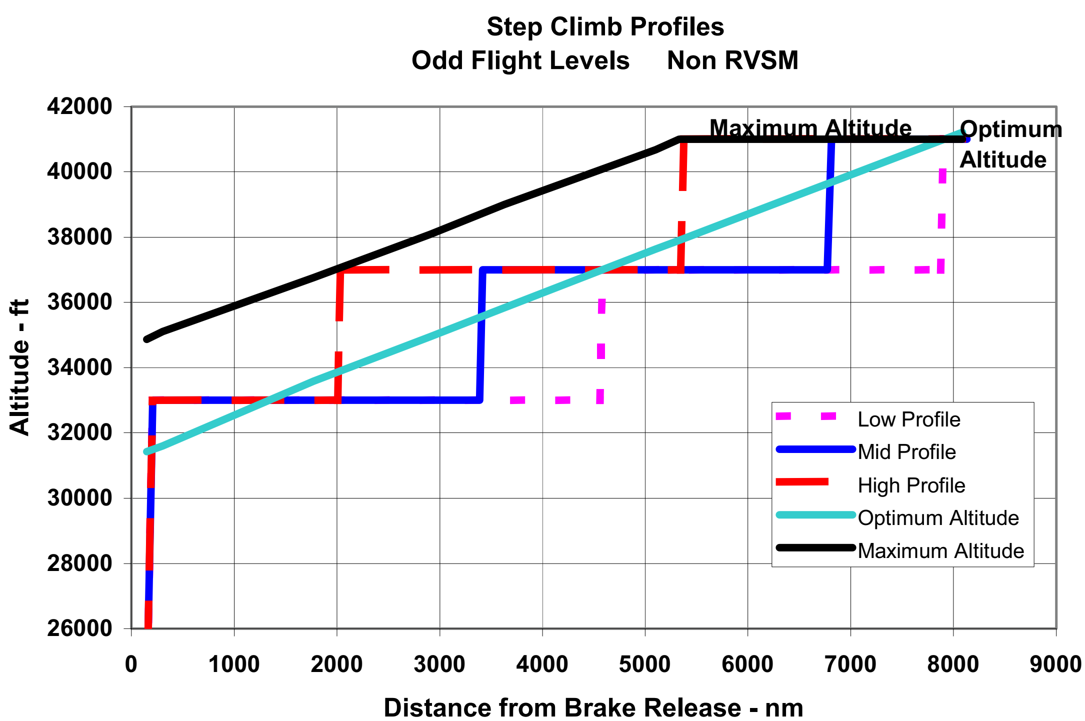
The **Low profile** initiates the step climb at the weight where the next available flight level is also the optimum flight level at that weight. Consequently the flight levels are always at or below the optimum. This has the advantage of better maneuverability margins and generally a better speed as it is closer to the crossover altitude.

The **high profile** initiates the step climb at the weight where the next available flight level is also the maximum flight level at that weight. The flight levels are mainly above the optimum and the aircraft will have decreased maneuverability and fly slower.

The **mid profile** initiates the step climb at the weight where the specific range at the next available flight level is better than that at the current flight level. This enables the flight profile to remain as close as practically possible to the optimum flight level. It is this technique that is recommended for best fuel economy, and is also very close to that required for best economics.

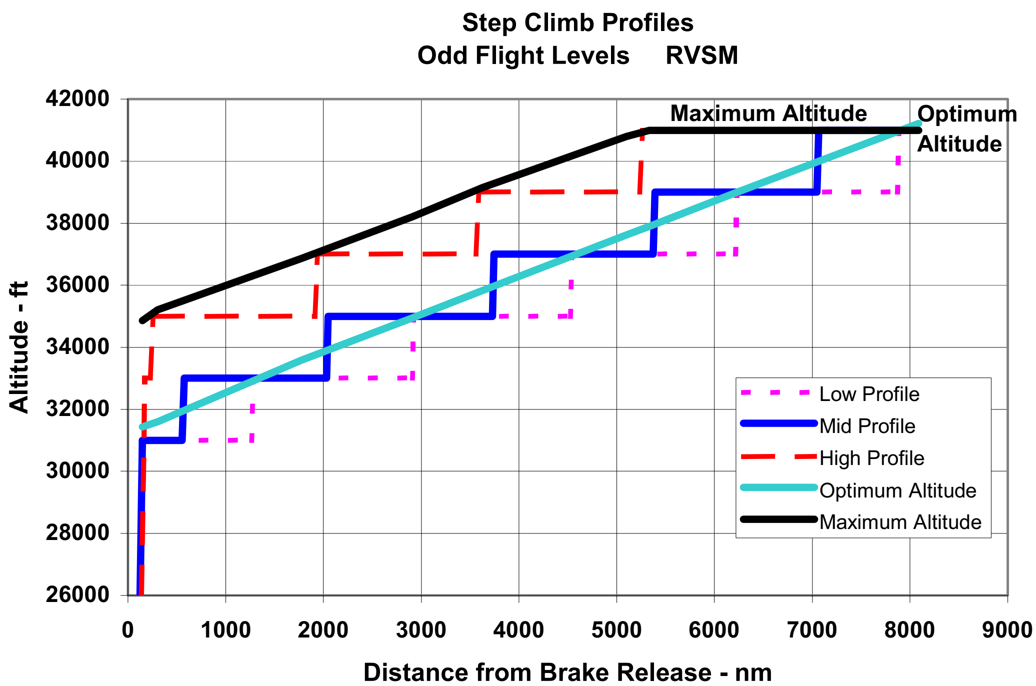
It is interesting to note that, in this case, the Mid profile step climb is made 1140nm before the Low Profile step climb and 1520nm after the High profile step climb.

The situation changes with odd flight levels:



Because of the different available flight levels, the step climbs are initiated some 1500nm further than the even flight level step climb points. However the relative merits of each profile remains the same.

With Reduced Vertical Separation Minima (RVSM) the difference between flight levels reduces from 4000 to 2000ft and this enables the aircraft profile to remain much closer to the optimum. In addition the high profile (depending on the aircraft) remains much higher than the optimum, increasing the fuel penalty. This profile is shown on the following page.



Thus pilots are advised to perform step climbs around the optimum altitudes. To facilitate this, the optimum weight for climb to the next flight level is given in most FCOM's (not A300/A310). An example is shown below.

A318/319/320/321 FLIGHT CREW OPERATING MANUAL	FLIGHT PLANNING CRUISE LEVEL	2.05.20 P 1	
		SEQ 205	REV 31

R **OPTIMUM WEIGHT FOR 4000 FEET STEP CLIMB**

R

STEP CLIMB FROM/TO	WEIGHT (1000 kg/1000 lb)					
	≤ ISA + 10		ISA + 15		ISA + 20	
	LR	M.78	LR	M.78	LR	M.78
310/350	74/163	75/165	74/163	75/165	74/163	75/165
330/370	68/149	68/149	68/149	68/149	67/147	68/149
350/390	61/134	62/136	61/134	62/136	61/134	62/136
370/410	55/121	56/123	55/121	56/123	55/121	56/123

On all Airbus FMS-equipped aircraft, the optimum altitude (OPT FL) and the maximum flight level (MAX FL) are displayed on the MCDU progress page. The recommended maximum altitude in the FMGC ensures a 0.3g buffet margin, a minimum rate of climb of 300ft/min at MAX CLIMB thrust and a level flight at MAX CRUISE thrust. Depending on weight and type, it is 2000 to 4000ft above the optimum altitude.

Typical cruise distances between 2000 foot altitude steps are shown in the following table:

Type	Distance - nm
A300	1000 - 1100
A310	1150 - 1250
A320	1200 - 1300
A330	1500 - 1650
A340	1500 - 1650
A340-500/600	1600 - 1700

For sector lengths greater than these, where ATC restrictions do not allow a change in cruise altitude from the initial requested level, the initial request should be the highest compatible with the maximum cruise altitude.

5.3.2.3 DELAYS IN ALTITUDE CHANGES

Let's consider an aircraft that is at flight level 330, which has, at that weight, an optimum flight level of 370. If it does not climb to FL 370 for ATC or other reasons, it will consume more fuel. The following table shows the difference in fuel burn for a 500nm still air cruise, when cruising at FL 330 instead of FL 370.

Aircraft Type	Fuel Increase (kg)	Fuel Increase (%)
A300B4-605R	238	5.2
A310-324	221	5.3
A318-111	150	6.2
A319-132	184	7.9
A320-211	158	6.2
A320-232	187	7.9
A321-112	155	5.5
A330-203	324	5.5
A330-343	342	5.6
A340-212	393	6.2
A340-313E	378	6.0
A340-500/600	336	4.1

Thus delaying a climb to a higher altitude has a significant impact on fuel burn.

5.3.2.4 OPTIMUM ALTITUDES ON SHORT STAGES

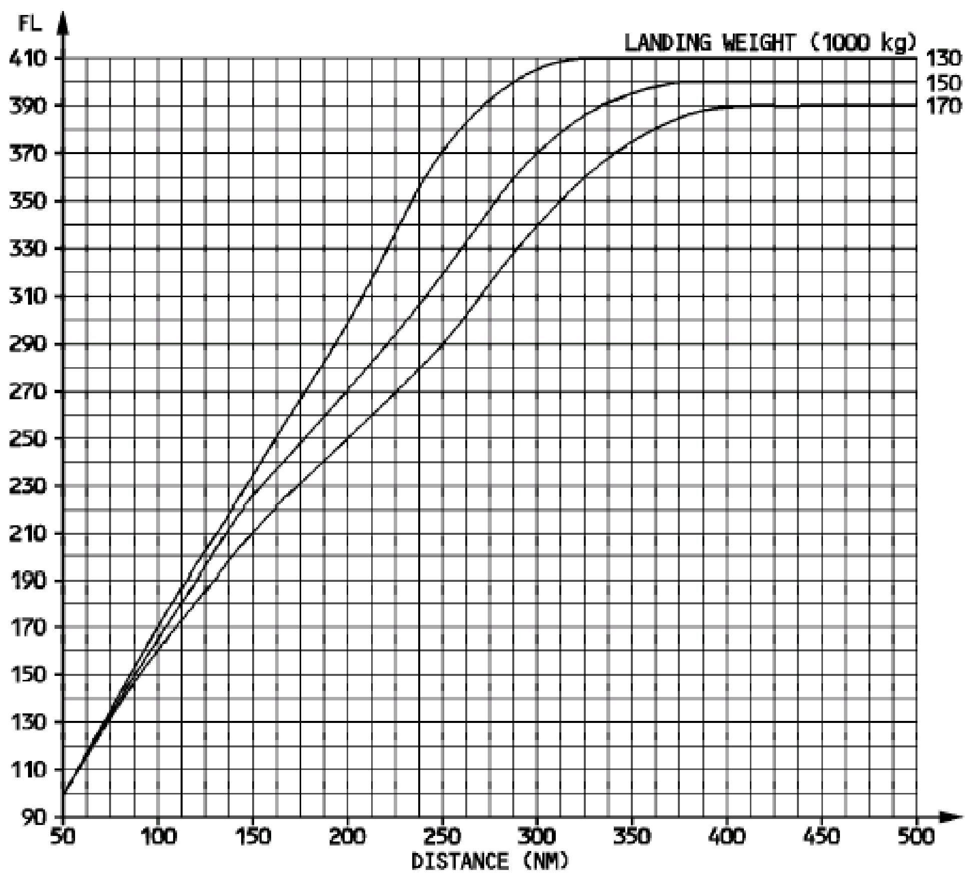
For short stages, the choice of cruise flight level is often restricted due to the necessary climb and descent distance. Airbus philosophy assumes a minimum 5 minute cruise sector, because a climb followed immediately by the descent is not appreciated by pilots, passengers or ATC.

If the stage length is of sufficient length that the optimum flight level can be reached, but the cruise is of short duration, then the benefits at this flight level will be marginal. It may even be worthwhile to cruise at one flight level lower, as the increased climb consumption offsets any reduced cruise consumption.

In the FCOM there is a chart showing the optimum altitude on a short stage. An example is shown below.

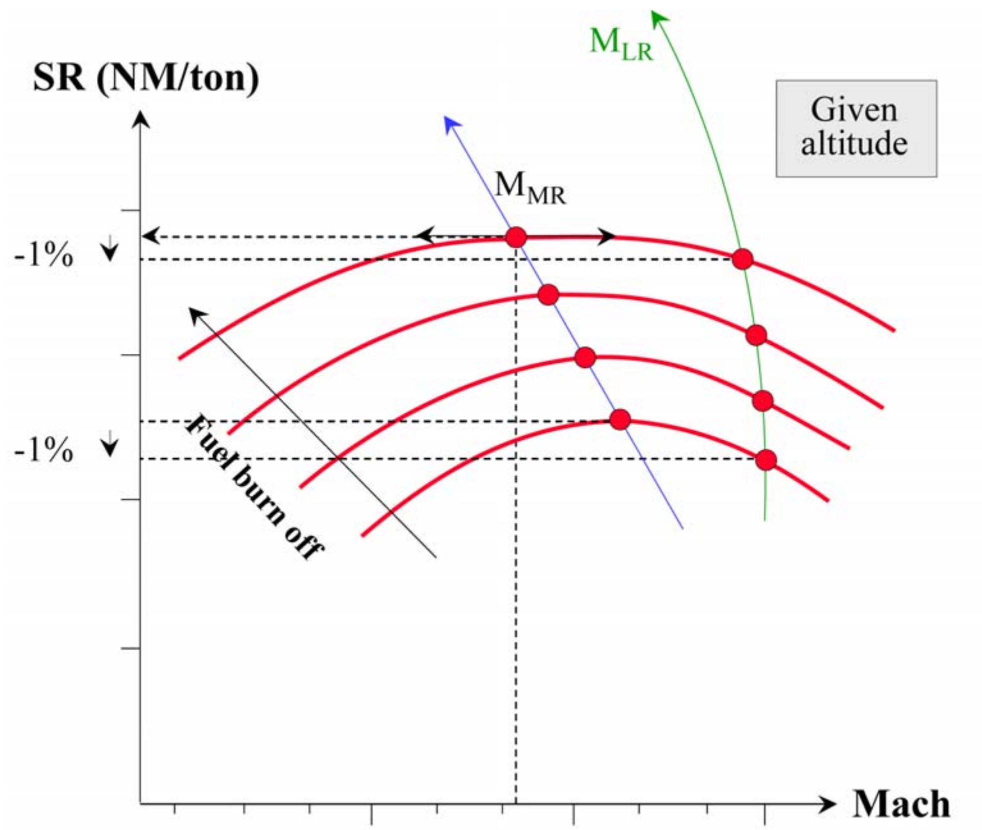
A330 FLIGHT CREW OPERATING MANUAL	FLIGHT PLANNING	2.05.20	P 4
	CRUISE LEVEL	SEQ 070	REV 06

OPTIMUM ALTITUDE ON SHORT STAGE



5.3.3 CRUISE SPEED OPTIMISATION

Having been given a flight level which may be a requested optimum altitude or one imposed by air traffic control, speed is the only remaining parameter that requires selection. The following picture shows the variation of Specific Range with Mach Number for different aircraft weights at a fixed altitude.

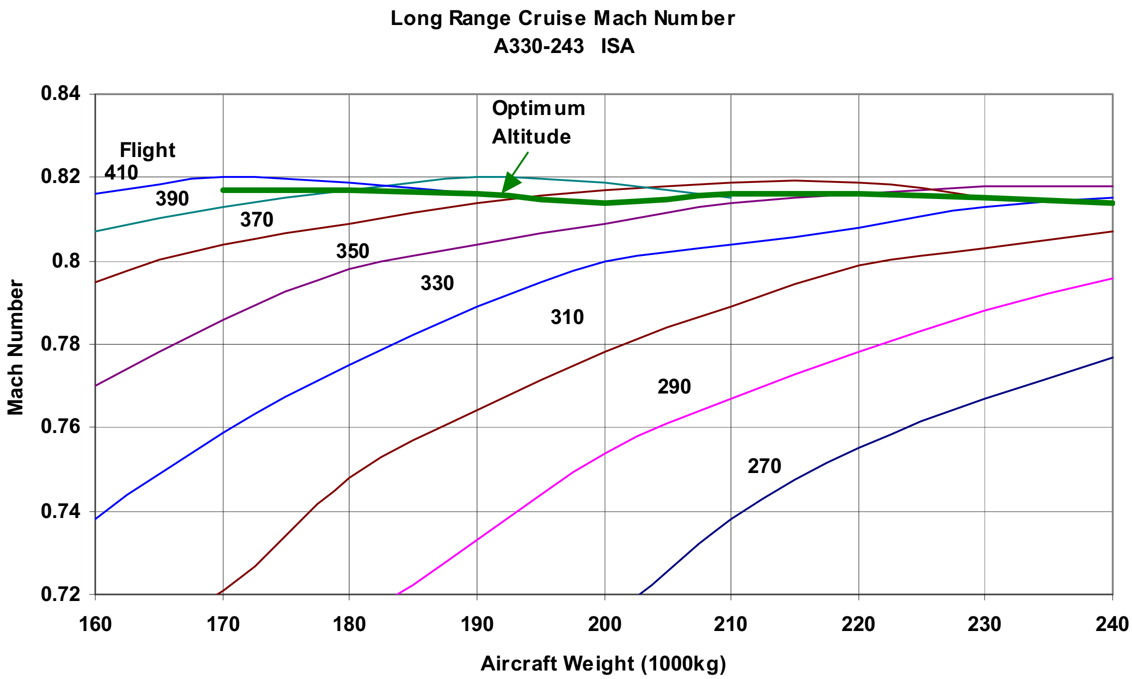


The Mach number, which gives the best specific range, can be determined. It is called the maximum range cruise Mach (M_{MR}). Nevertheless, for practical operations, a long-range cruise procedure is defined which gains a significant increase in speed compared to M_{MR} with only a 1% loss in specific range. Like the M_{MR} speed, the M_{LRC} speed also decreases with decreasing weight, at constant altitude.

A more detailed explanation of this can be found in "Getting to Grips with Aircraft Performance"

The following chart shows the typical variation of the Long Range Cruise Mach Number with aircraft weight for various flight levels. Also plotted on this chart is the optimum altitude line. This shows that there is not much variation in the long-range cruise mach number at these altitudes.

It would therefore be possible to fly a constant Mach number procedure instead of the variable LRC speed procedure. In order to save fuel however, the exact LRC speed should be maintained.

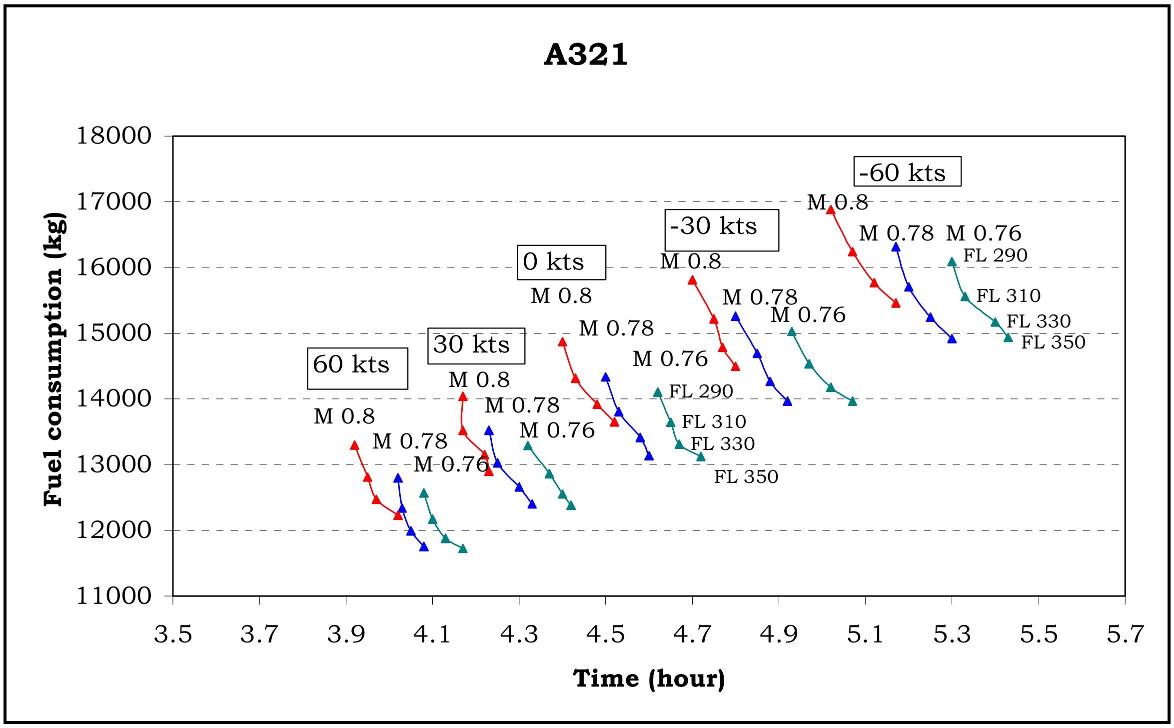


The Long Range Cruise Speed can be found in the Cruise tables in the FCOM.

5.3.4 WIND INFLUENCE

Wind can have a significant influence on fuel burns. Nowadays, meteorological forecasts are very reliable and its integration into the FMS provides accurate information to crews. Hence the latter best perform flight planning with a view towards fuel savings.

The effect of the wind on trip time and fuel is shown on the following chart, which gives fuel consumption and time for a 2000nm sector, with respect to flight levels, Mach number and wind (tailwind positive) for a fixed take-off weight.

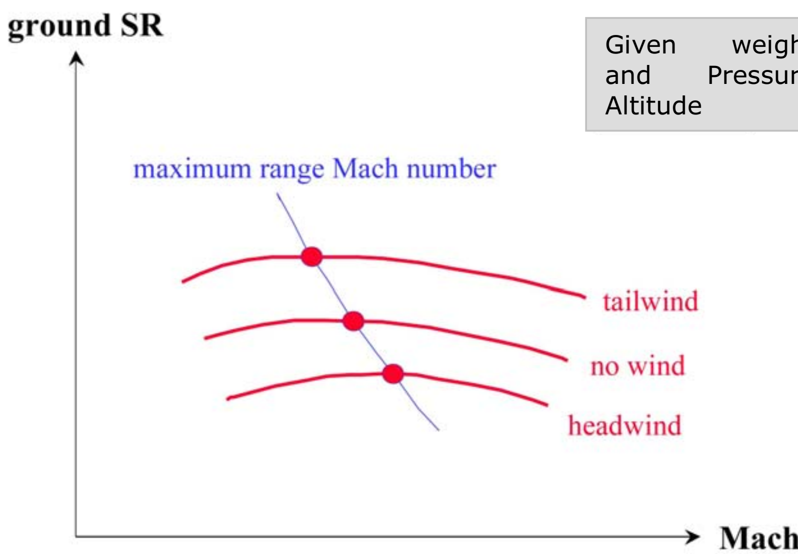


This plot graphically shows the magnitude of the significant changes in fuel consumption and time due to winds. FCOM Tables show the equivalent still air distances for any ground distance/wind combination.

However the winds can affect the performance optimization as well as changing the effective still air distance. The M_{MR} (or M_{LRC}) value varies with headwind or tailwind, due to changes in the SR.

The effect of a tailwind is to increase the ground speed, and therefore the SR, by the ratio of ground speed to airspeed. A given wind speed therefore has a larger effect at the lower airspeeds, which changes the optimum speed.

The following chart shows the Maximum Range Mach number versus wind variations.



M_{MR} and wind influence

This shows that

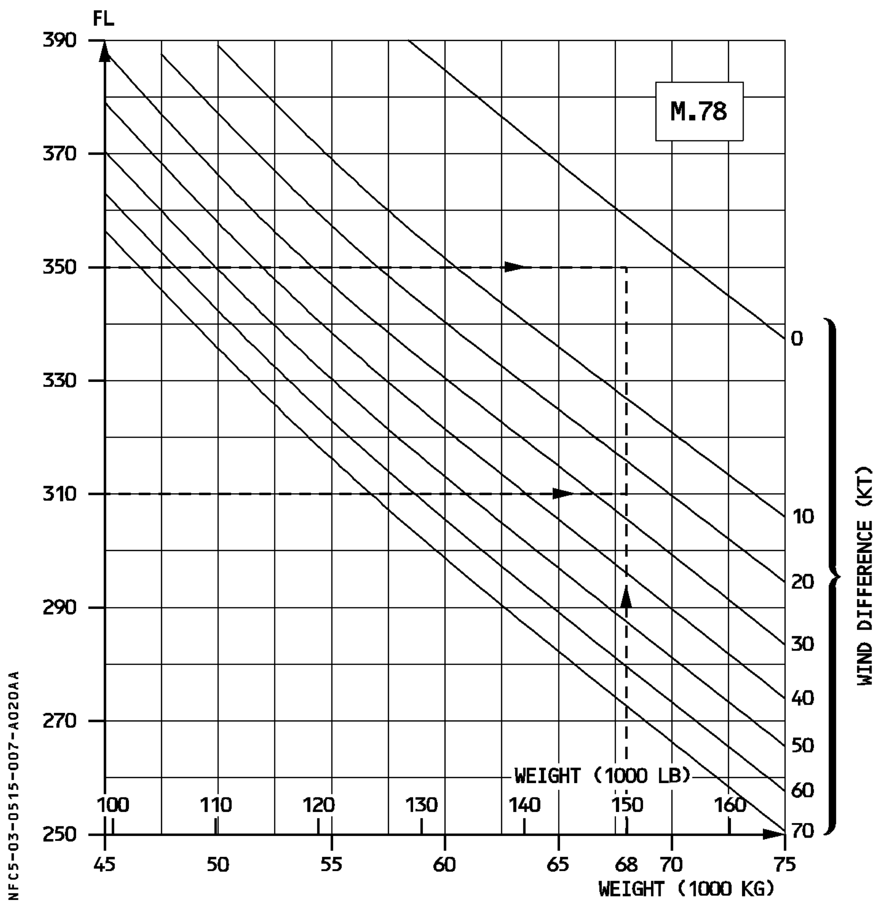
Tailwinds	increase the specific range and lower the speeds
Headwinds	decrease the specific range and raise the speeds.

The wind speed can be different at different altitudes. For a given weight, when cruise altitude is lower than optimum altitude, the specific range decreases. Nevertheless, it is possible that, at a lower altitude with a favorable wind, the ground specific range improves. When the favorable wind difference between the optimum altitude and a lower one reaches a certain value, the ground-specific range at lower altitude is higher than the ground-specific range at optimum altitude. As a result, in such conditions, it is more economical to cruise at the lower altitude.

There is information in the most FCOM's (not A300/310) to indicate the amount of favorable wind, necessary to obtain the same ground-specific range at altitudes different from the optimum. If the wind is more favorable then it is beneficial to fly lower. The following shows such a page:

A319/320/321 FLIGHT CREW OPERATING MANUAL	IN FLIGHT PERFORMANCE CRUISE	3.05.15 P 7	SEQ 020 REV 24

WIND ALTITUDE TRADE FOR CONSTANT SPECIFIC RANGE



GIVEN : Weight : 68000 kg (150 000 lb)
Wind at FL350 : 10 kt head

FIND : Minimum wind difference to descend to FL310 : (26 − 3) = 23 kt

RESULTS : Descent to FL310 may be considered provided the tail wind at this altitude is more than (23 − 10) = 13 kt.

5.3.5 MANAGED MODE

The flight management system (FMS) optimizes the flight plan for winds, operating costs and suggests the most economical cruise altitude and airspeed, depending on the cost index chosen by the airline. An airline that wants to save fuel has to choose a low cost index. The next part intends to highlight the impact of the cost index on fuel consumption and on trip time. More complete information can be found in the "Getting to Grips with Cost Index" brochure.

5.3.5.1 ECONOMIC MACH NUMBER

Long-range Cruise Mach number was considered as a minimum fuel regime. If we consider the Direct Operating Cost instead, the **Economic Mach number** (**M_{ECON}**), can be introduced.

Direct Operating Costs (DOC) are made up of fixed, flight-time related and fuel-consumption related costs. As a result, for a given trip, DOC can be expressed as:

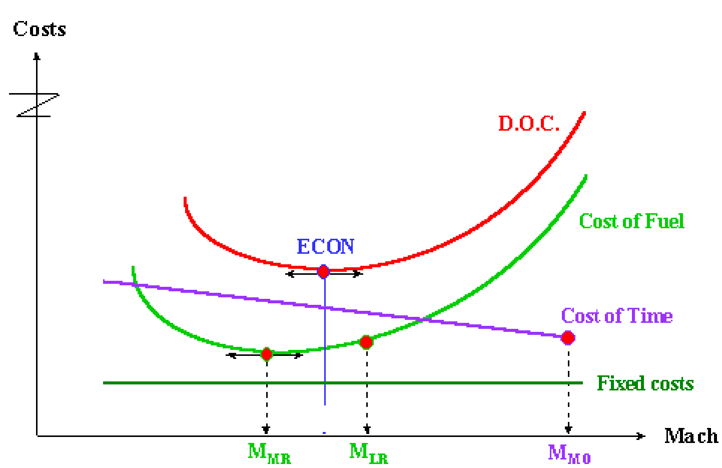
$$\boxed{DOC = C_C + C_F.\Delta F + C_T.\Delta T}$$

where C_C = fixed costs

C_F = cost of fuel unit ΔF = trip fuel

C_T = time related costs per flight hour ΔT = trip time

As DOCs are calculated per nautical mile, it is possible to plot fuel-related costs, flight-time related costs, and direct operating costs based on Mach number .



Minimum fuel costs correspond to the Maximum Range Mach number. The minimum DOC corresponds to a specific Mach number, referred to as Econ Mach (M_{ECON}).

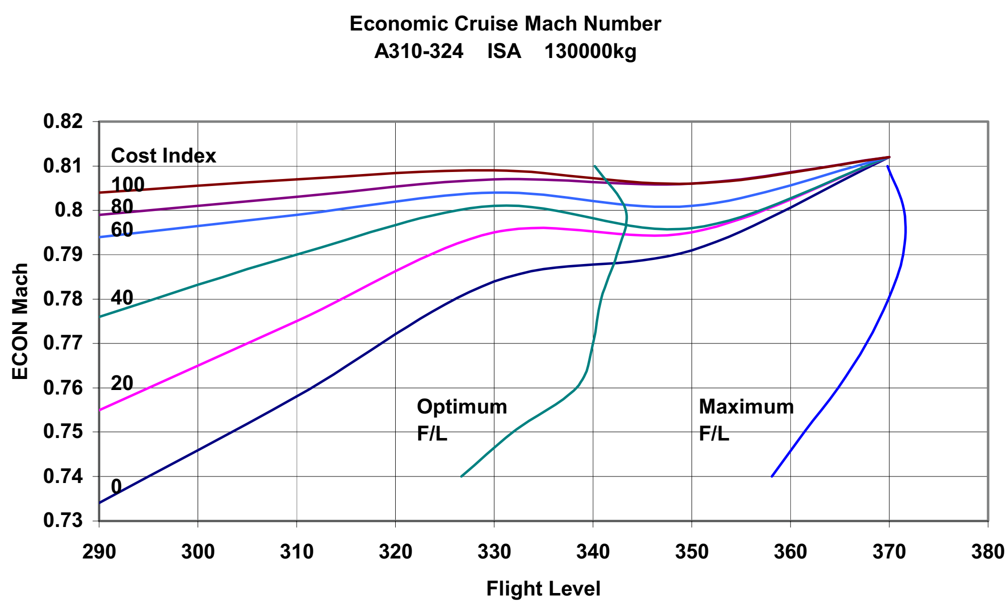
$$\begin{array}{llll} FL = \text{constant} & \text{weight} \searrow & \Rightarrow M_{ECON} \searrow \\ \text{weight} = \text{constant} & \text{FL} \nearrow & \Rightarrow M_{ECON} \nearrow \end{array}$$

The M_{ECON} value depends on the time and fuel cost ratio. This ratio is called **cost index** (**CI**), and is usually expressed in kg/min or 100lb/h:

$$\text{Cost Index (CI)} = \frac{\text{Cost of time}}{\text{Cost of fuel}} = \frac{C_T}{C_F}$$

Depending on the cost index, the predicted aircraft and atmospheric conditions, the optimum altitude and the economic Mach number are computed. From then on, fuel consumption depends only of the chosen cost index.

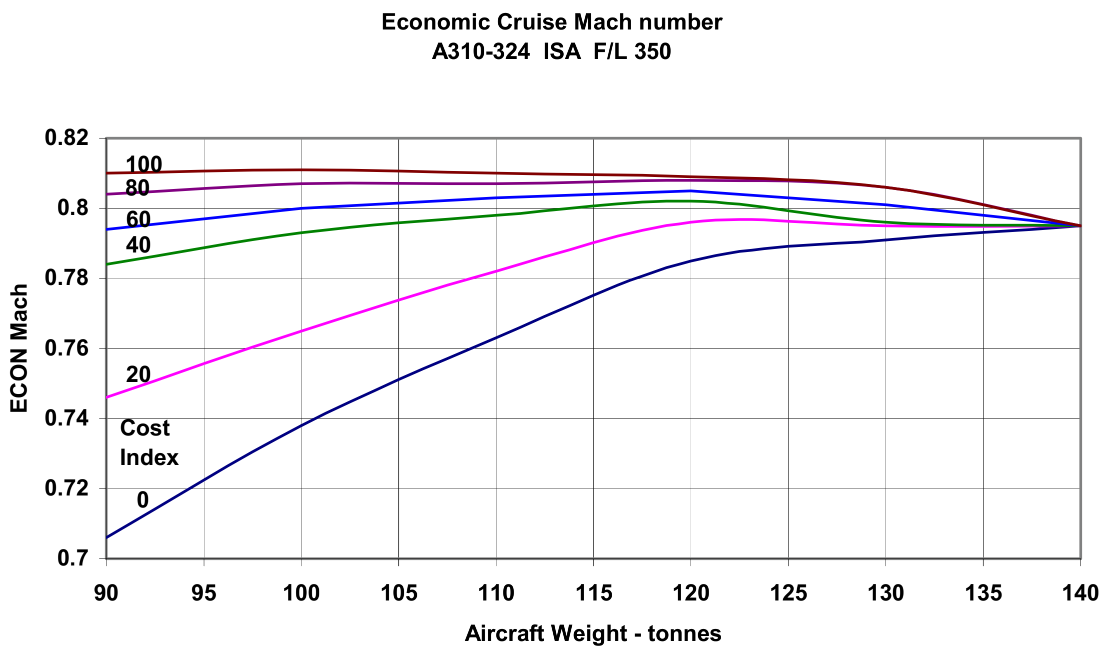
The following chart shows the economic Mach number variation with flight level for different cost indices.



This shows the general trend, common with all aircaft, of increasing economic Mach number with flight level.

The charts also show large economic Mach number changes with flight level for low cost indices, whereas it is rather constant for high cost indices. The economic Mach is very sensitive to the cost index when flying below the optimum altitude.

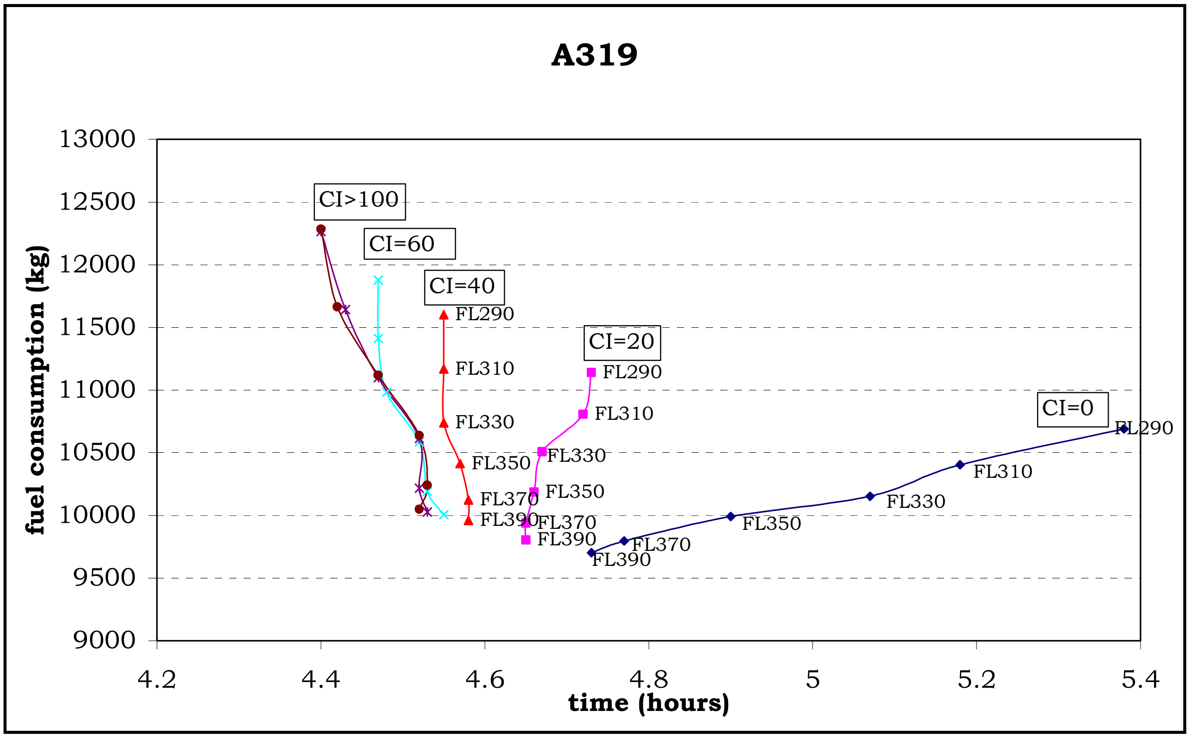
The effect of weight variation at a fixed flight level is shown below.



The charts show that for high cost indices, the economic Mach number stays fairly constant throughout the flight. Nevertheless, for a low cost index, the economic Mach number reduces significantly as the weight reduces. This is quite normal as low cost indices favor fuel consumption at the expense of time. Moreover, we notice that for low cost indices, a small cost index increment has a far-reaching influence on the economic Mach number, and hence on flight time. These trends are typical of all aircraft.

5.3.5.2 TIME/FUEL RELATIONSHIP

To know whether the fuel economies at low cost indices are worthwhile, the impact of cost index on time has to be considered. The following graph show both trip fuel and time for different flight levels and cost indices. The shape of this chart is typical of all types.



As it can be seen, it is not really advantageous to fly at very low cost indices as fuel savings are not significant compared to time loss. Although using slightly higher fuel, a slightly higher cost index gives significant time gains.

For instance, for the A319, increasing the cost index from 0 to 20 reduces the block time by 15 minutes (5%) for a fuel burn increase of only 200kg (2%) on a 2000nm sector.

5.3.6 EFFECT OF SPEED INCREASE ON MANAGED MODE

Flying at a given cost index rather than at a given Mach number provides the added advantage of always benefiting from the optimum Mach number as a function of aircraft gross weight, flight level and head/tailwind components.

This means the ECON mode ("managed" mode) can save fuel relative to fixed Mach schedules ("selected" mode) and for an equivalent time.

One can wonder whether selecting a higher Mach number than the one chosen by the FMS has a significant impact on fuel consumption. Imagine an aircraft flying at flight level 370, in managed mode and at the optimum weight of FL370. The FMS computes the optimum speed based on cost index, temperature and wind. If the pilot selects another (higher) Mach number, the fuel consumption will increase.

The following tables show the effect of such a speed increase.

		Economic Mach No + 0.005			Economic Mach No + 0.01		
		Fuel Penalty		∆Time	Fuel Penalty		∆Time
Aircraft	Sector	Kg	%	Min	Kg	%	Min
A300-605	2000 Nm	110	0.4	1	230	0.9	3
A310-324	2000 Nm	90	0.4	1	430	2.0	8
A318	1000 Nm	30	0.5	1	60	1.0	1
A319	1000 Nm	20	0.2	1	40	0.6	2
A320	1000 Nm	20	0.3	1	40	0.7	2
A321	1000 Nm	10	0.1	1	30	0.4	1
A330	4000 Nm	150	0.3	3	330	0.6	6
A340-212	6000 Nm	390	0.5	5	790	0.9	10
A340-313E	6000 Nm	380	0.4	5	900	1.0	10
A340-500	6000 Nm	1050	0.9	5	2540	2.1	9
A340-600	6000 Nm	820	0.7	4	2060	1.8	9

We notice that although decreasing block times, the increase of Mach number above the Optimum speed can result in significant increases in fuel burn. Pilots hence have to be patient and should not change the Mach number even when under the impression that the aircraft does not fly fast enough.

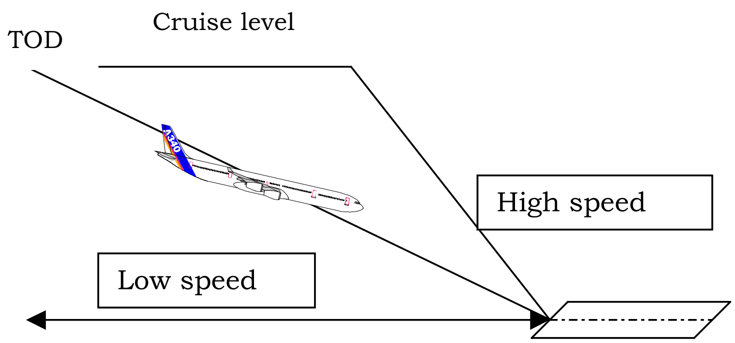
Moreover, when possible, the managed mode must be kept.

5.4 DESCENT

5.4.1 INTRODUCTION

Depending on the descent law, flight paths do vary in steepness.

Indeed, the higher the speed law, the steeper the flight path.



Descent profiles.

Descents are normally performed in three phases on a constant IAS/Mach descent speed schedule, as follows:

- Constant Mach number is maintained until the crossover altitude
- Constant indicated air speed is maintained down to 10000ft
- 250 KT indicated air speed (IAS) is maintained below flight level 100, until the aircraft decelerates for landing

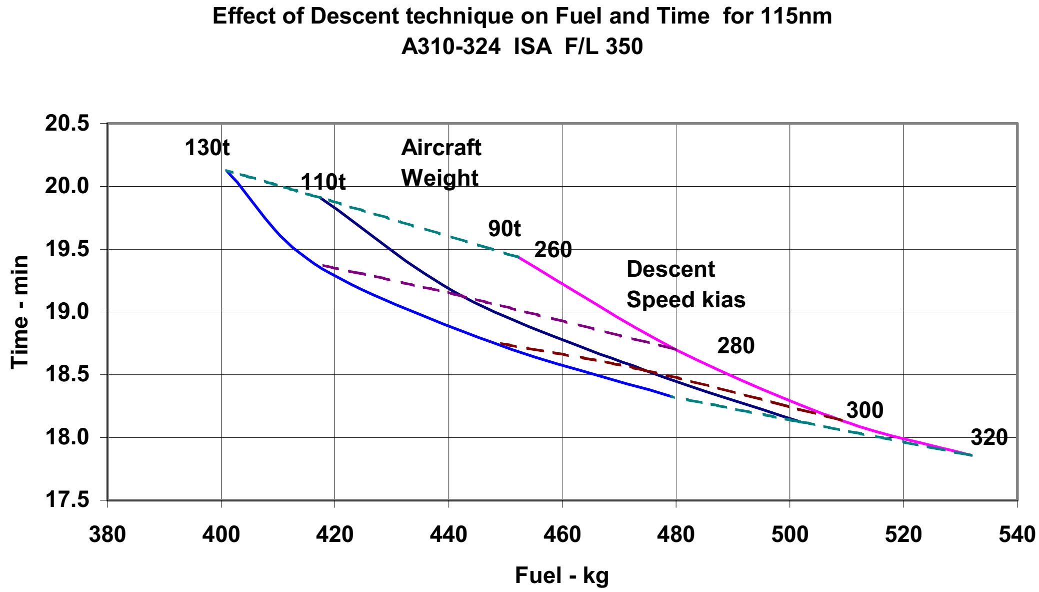
The engine thrust is normally set to flight idle for the descent and the speed is controlled by the aircraft attitude. In these conditions higher weights increase the descent distance because of the reduction of descent gradient (which equals [thrust-drag]/weight in stabilized flight). This also increases the descent fuel.

However a descent from high altitudes at low weight may lead to a gradient of descent that results in an excessive cabin rate of descent. In these cases the rate of descent is reduced by application of power, until a flight idle descent can be continued. This results in what is known as the re- pressurization segment, and this can reverse the weight-descent distance relationship.

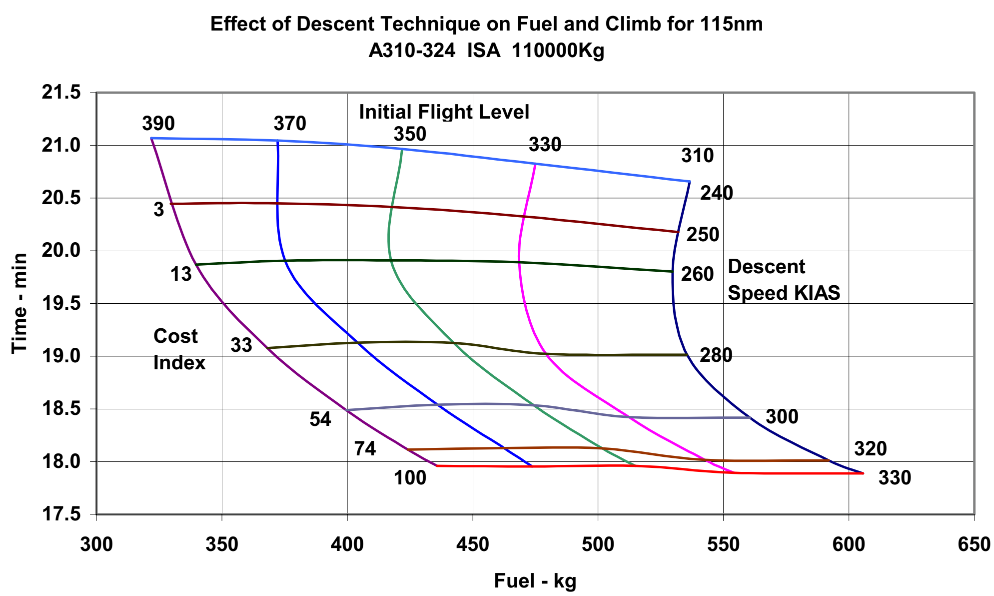
To correctly evaluate the effects of descent techniques, cruise and descent flight must be viewed in relation to each other. A short descent distance for example extends the cruise distance. One has therefore to consider in addition to the descent, a small portion of the cruise to the same distance.

5.4.2 THE EFFECT OF DESCENT TECHNIQUES ON FUEL BURN

An evaluation has been made of the fuel burn to a constant distance, and this now shows that the higher weights use less fuel. Lower speeds, although requiring more fuel for the descent only requires less total fuel because of the longer descent distance. This is shown in the following chart.



At a fixed weight, the following chart shows that the minimum fuel occurs at a descent speed of 240kias to 280kias, dependant on flight level.



However there is a significant time penalty at these speeds.

Note that the effect of the descent Mach number is very dependant on cruise flight level and descent speed, but is relatively small compared to the descent speed effect, and is not fully investigated here.

These descent charts are typical of the other Airbus aircraft. Generally they show a minimum fuel speed of 260 to 280 kts for flight level 310, reducing to 240kts for flight level 390. The exceptions are the A318, A319, A320 and A330, which show the minimum fuel at 240kias for all flight levels which is slightly lower than the other aircraft at FL310.

Appendix B presents some examples of these descent charts for other Airbus aircraft.

The following tables show, for various Airbus aircraft, the descent time and fuel variations for a fixed distance, from FL 350, relative to a 300kias reference speed.

Type	∆Fuel – kg					
	240KT	260 KT	280 KT	300 KT	320 KT	330/340KT *
A300	-55	-60	-30	0	25	35
A310	-55	-60	-30	0	25	40
A318, 319, 320	-50	-40	-20	0	20	25
A321	-35	-40	-20	0	20	35
A330	-110	-105	-60	0	50	70
A340–200/300	-70	-90	-50	0	50	75
A340-500/600	-125	-130	-70	0	70	100

Type	∆Time – minutes					
	240 KT	260 KT	280 KT	300 KT	320 KT	330/340KT *
A300	2.7	1.5	0.6	0	-0.4	-0.6
A310	2.4	1.4	0.6	0	-0.4	-0.6
A320 family	2.6	1.4	0.6	0	-0.4	-0.6
A330	3.5	2.0	0.8	0	-0.6	-0.8
A340–200/300	3.2	1.8	0.8	0	-0.6	-0.8
A340-500/600	3.3	1.9	0.8	0	-0.6	-0.8

* A300/A310/A320 330kias A330/A340 340kias

Comparing these tables to the equivalent climb comparison tables in chapter 5.2.4, it can be noticed that descent techniques often have a greater effect on fuel and time than climb techniques.

5.4.3 MANAGED MODE DESCENT

The FMS computes the Top Of Descent (TOD) as a function of the cost index. We notice that the higher the cost index:

The steeper the descent path (the higher the speed)

The shorter the descent distance

The later the top of descent.

Descent performance is a function of the cost index; the higher the cost index, the higher the descent speed. But contrary to climb, the aircraft gross weight and the top of descent flight level appear to have a negligible effect on the descent speed computation.

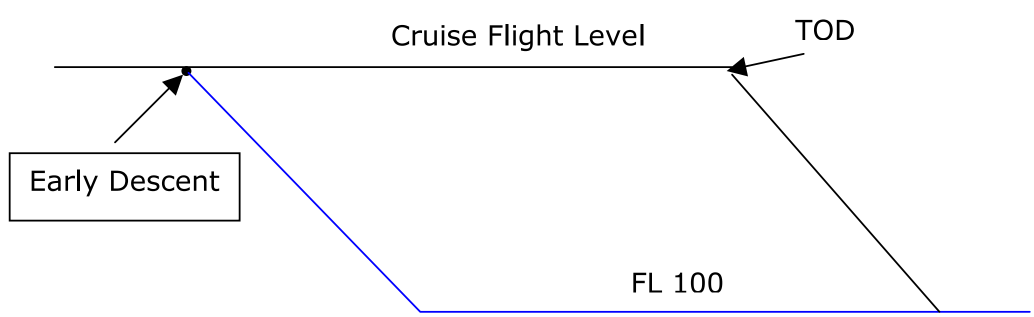
It can be noticed that time to descent is more dependant on cost indices than the time to climb.

On the Effect of Descent Technique on Fuel and Time chart, the cost index has been annotated for each speed. It can be seen that the minimum fuel is at a CI of 0, and the minimum time occurs with a high CI, as would be expected.

For the A300, A310 and A320 family the speed at zero cost index is about 250kias. For the A330/340 it is about 270kias. Max speed normally corresponds with a high cost index of 60 to 120. Once more it can be seen how, in the managed mode, the cost index is used to choose the balance between fuel burn and flight time.

5.4.4 EARLY DESCENT

If the aircraft begins its descent too early, the aircraft would leave its optimal flight level, where fuel consumption is at its best, and would have to cruise at a lower altitude to arrive at the same point.



Two descent situations were simulated:

• Descent commenced 15nm (or about 2 minutes) early followed by a level-off at FL100.

• Cruise continued from the early descent point until the optimum start of descent, followed by the descent

At 10000ft, the cruise speed could be selected between LRC and max speed. If in managed mode, one could continue at the same cost index, or select the 250kias below 10000ft limiting speed. The following table compares the two options.

Aircraft	250KIAS at FL100		LRC at FL100	
	∆Fuel – kg	∆Time – min	∆Fuel – kg	∆Time – min
A300-600	70	1.1	95	0.4
A310	70	1.1	90	0.3
A320 family	50	1.1	65	0.2
A330	80	1.2	100	0.5
A340-200/300	95	1.2	105	0.5
A340-500/600	135	1.2	125	0.5

Cruising faster at 10000ft reduces the time penalty at the expense of fuel.

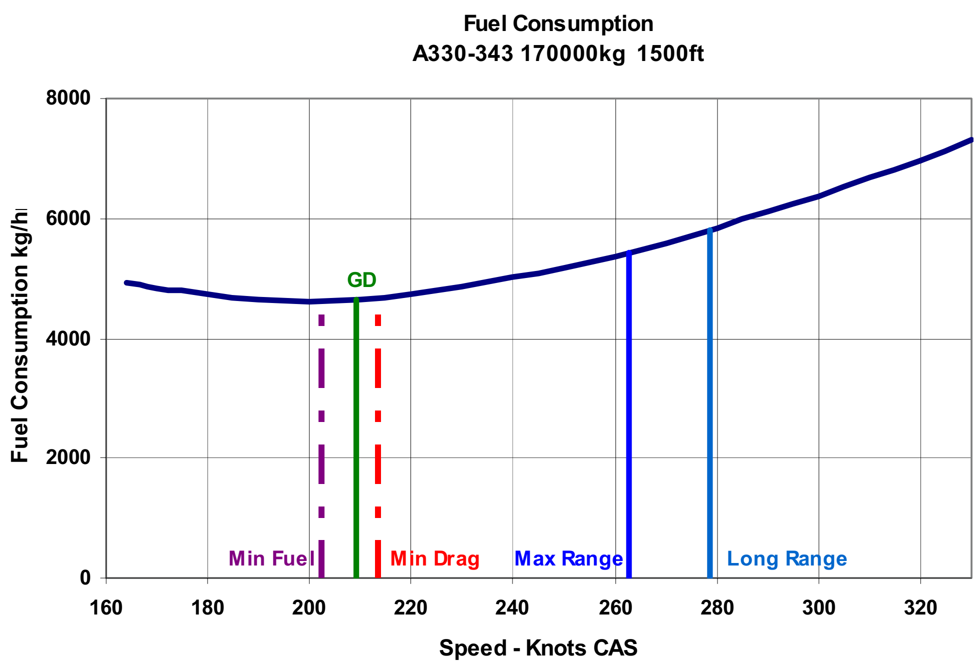
After a long flight with an A340–500 or –600, starting the descent some 100nm early would not appear to be significant in the overall flight. However this can result in a 900kg fuel burn increase and 8 minutes longer block time.

5.5 HOLDING

5.5.1 INTRODUCTION

When holding is required, it is generally flown on a "race track pattern", composed of two straight legs plus two 180 degree turns. In a hold the distance covered is not the primary objective. On the contrary, the knowledge of the maximum holding time (maximum endurance) is a determining factor for any diversion decision. As a result, it is important, during holding, to try to minimize fuel by simply minimizing fuel flow.

For all aircraft, the minimum fuel consumption speed is very close to the maximum lift-to-drag ratio (Green Dot) speed as shown below. As a result, in clean configuration, the standard holding speed is selected equal to **green dot** speed (GD).



Holding patterns may be quite limiting around certain airports due to obstacle proximity. Therefore, green dot is sometimes too high, especially during turn phases where the bank angle can be too significant. As it is not possible to significantly reduce the speed below green dot in clean configuration, slats may be extended and a holding done in **CONF1** at "**S**" speed. (min slat retraction speed Conf 1 to Conf clean).

At other airports, Air Traffic Control may require the hold to be performed at a certain speed, and it may not be possible fully optimise the fuel burn. In order to allow flexibility in planning and operations, the FCOM has four different holding speed and configuration combinations, adapted to each type of aircraft.

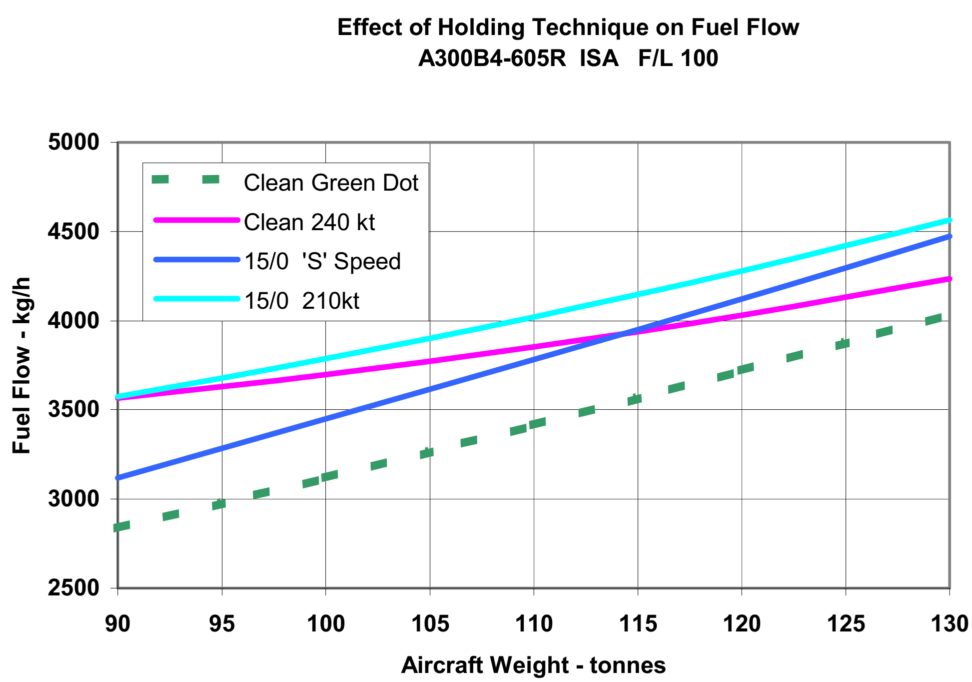
The following table gives the configurations and speeds for each type.

Aircraft types	First Flap/slat Configuration		Clean configuration	
A300-600	210kts	S speed	240kts	Green Dot
A310	170kts	S speed	210kts	Green Dot
A320 Family (CFM)	170kts	S speed	210kts	Green Dot
A320 Family (IAE)	170kts	S speed	210kts	Green Dot + 20
A330	170kts	S speed	210kts	Green Dot
A340-200/300	210kts	S speed	240kts	Green Dot
A340-500/600	240kts	S speed	-	Green Dot

For the A300/A310 the first configuration is flap 15, slat 0. For the other aircraft this is Conf 1. Note that the fourth combination for the A340-500/600 is Configuration 2 at 210kts.

5.5.2 VARIOUS CONFIGURATION / SPEED COMBINATIONS

The following graphs show the holding fuel flow variation with weight for the four different holding configurations. This is done at an altitude of 10000ft.



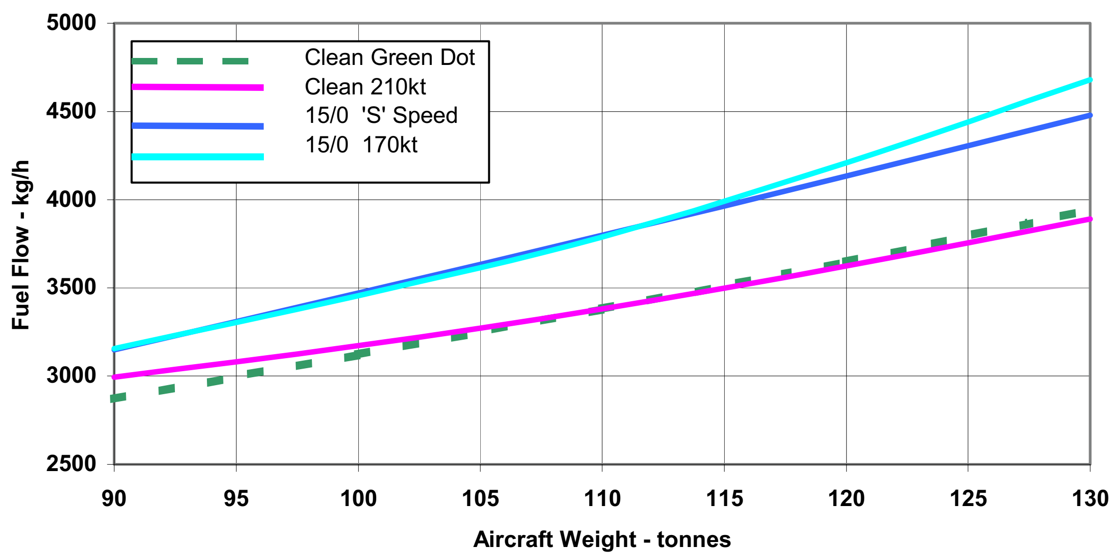
This graph is for an **A300** and it shows the advantage of holding in a clean configuration at the green dot speed. The clean configuration fixed speed of 240kt is significantly higher than the green dot speed; hence the large increase in fuel flow with this technique. The 15/0 configuration with a fixed speed of 210kt is also significantly higher than the 'S' speed, hence higher fuel flows.

The large variation in fuel flow shows how important it is to use the right configuration and speed, compatible with the other operational requirements.

The **A340-200/300** schedules the same hold speeds as the A300, and the graphs have a similar form with a large increase in fuel flow at low weights with the fixed speed techniques. However at high weights the difference is much smaller. There is also a large increase when using Conf 1. Once more holding clean at green dot speed gives the lowest fuel flow.

The following graph is for the **A310** and this shows completely different characteristics because of the lower fixed speeds used in each configuration.

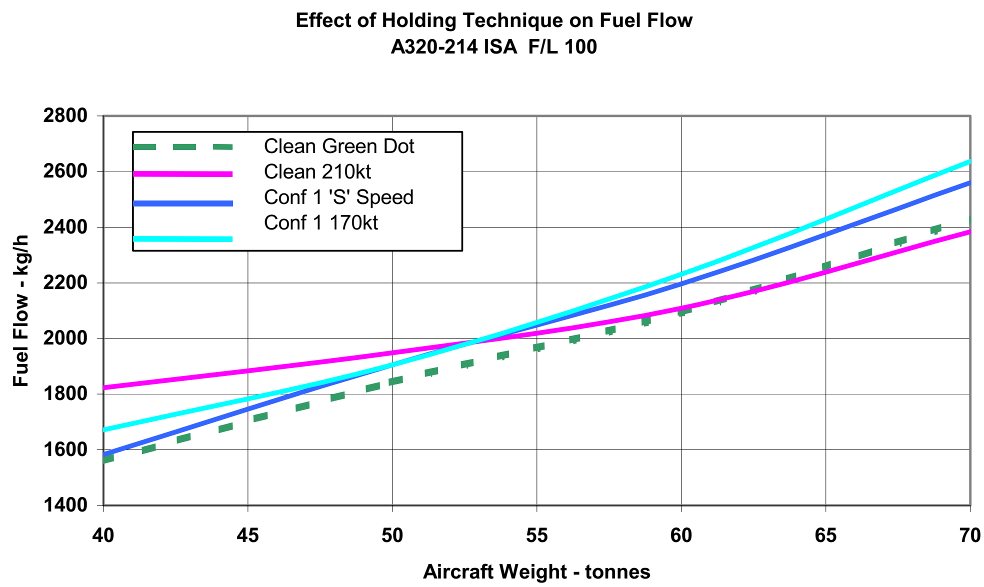
Effect of Holding Technique on Fuel Flow
A310-324 ISA F/L 100



Each configuration shows very similar fuel flow, whichever speed technique is used. The clean configuration green dot speed still represents the best single choice for lowest fuel burn over the normal holding weight range.

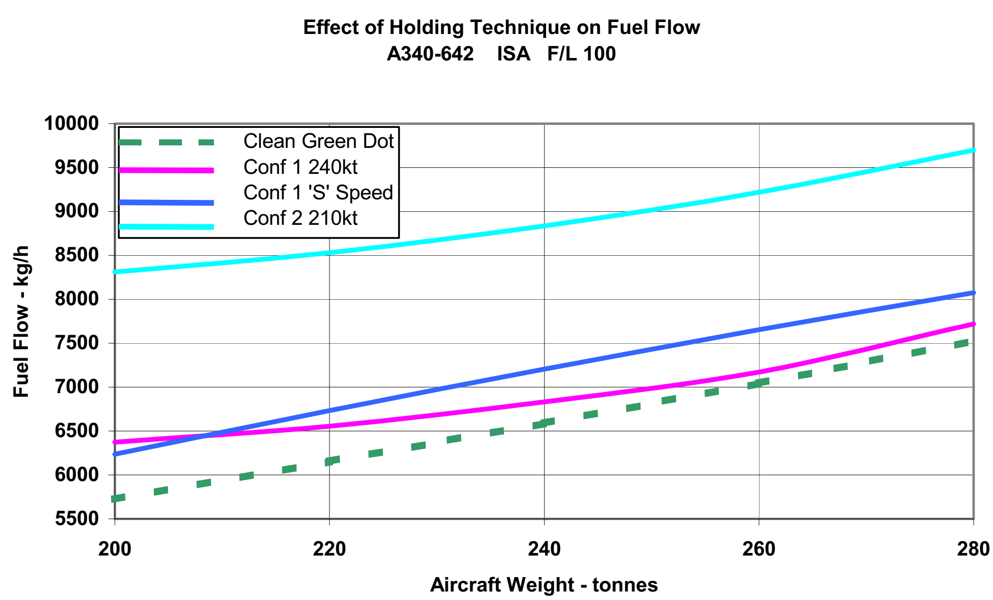
The **A330**, which has the same hold speed schedules shows the same characteristics, with clean configuration at green dot speed being marginally better than clean configuration at 210kt over the normal holding weight range.

The **A320** family shows a completely different set of characteristics as shown in the graph on the next page.



The variation of different techniques is very weight sensitive. However it is still the clean configuration at green dot speed that gives the lowest fuel flow. This picture is typical of all the A320 family.

Finally the **A340-500/600** has another set of configuration/speed combinations and the following graph shows its different characteristics, but the basic concept that the clean configuration and green dot is the best combination still remains true.



There is also **altitude** to be considered, although it is often not the operator's decision what flight level to hold at. Altitude has different effects on the fuel flow, depending on the airframe/engine combination. However, whatever the altitude effect, it generally affects all techniques equally; generally the higher the hold altitude the lower the fuel flow. This however is true only up to a certain altitude and this varies with each type.

The following table shows this altitude effect for a hold in the clean configuration at green dot speed. The holding fuel flow is compared with the lowest for the flight levels considered for each type, and the difference expressed as a percentage.

Flight Level	50	100	150	200	250	300	350	400
A300B4-605R	4	2	1	0	3	8	16	
A310-324	11	5	2	0	0	5	9	23
A318-111	13	8	4	2	1	0	0	5
A319-112	19	11	3	1	0	1	0	4
A320-214	13	5	3	1	1	1	0	2
A320-232	7	5	5	5	2	0	4	11
A321-211	14	11	8	3	0	1	5	
A330-203	2	1	0	0	2	4	8	18
A330-223	9	9	5	2	0	1	6	14
A340-343	10	5	1	0	0	2	7	16
A340-212	3	2	0	0	2	3	5	
A340-313E	2	1	0	0	2	3	5	
A340-642	6	2	0	1	2	3	4	11

In order to allow an assessment of the sensitivity of each aircraft type to different hold techniques, the following table shows the **extra fuel** required to hold for 15 minutes at 10000ft in the first flap configuration at 'S' speed, compared to Conf clean at green dot speed.

Effect of Holding in First flap Setting at 'S' speed compared with Clean at Green Dot speed

Aircraft types	Fuel Increase (kg) Low Holding Weight	Fuel Increase (kg) High Holding Weight
A300B4-605R	70	110
A300B4-622R	110	190
A310-324	70	135
A318	5	10
A319	10	30
A320	10	30
A321	30	50
A330-203	135	175
A330-223	175	205
A330-343	145	175
A340-212	170	230
A340-313	125	175
A340-642	130	150

The table shows that the green dot speed/clean configuration combination enables significant savings to be made.

However, green dot speed increases with weight and can become higher than the maximum recommended speeds, which are listed below:

Levels	ICAO	PAN-OPS	FAA	France
Up to 6,000 ft inclusive	230 KT	210 KT	200 KT	220 KT
Above 6,000 ft to 14,000 ft inclusive	230 KT	230 KT	230 KT	220 KT
Above 14,000 ft to 20,000 ft inclusive	240 KT	240 KT	265 KT	240 KT
Above 20,000 ft to 24,000 ft inclusive	265 KT	240 KT	265 KT	240 KT
Above 24,000 ft to 34,000 ft inclusive	265 KT	240 KT	265 KT	265 KT
Above 34,000 ft	M 0.83	240 KT	265 KT	M 0.83

If green dot is higher than these maximum recommended speeds, it is advised to hold in configuration 1 at "S" speed below 20000ft: keeping clean configuration coupled with a speed reduction would save fuel but would decrease the speed margins which are especially important in turbulent conditions.

5.5.3 LINEAR HOLDING

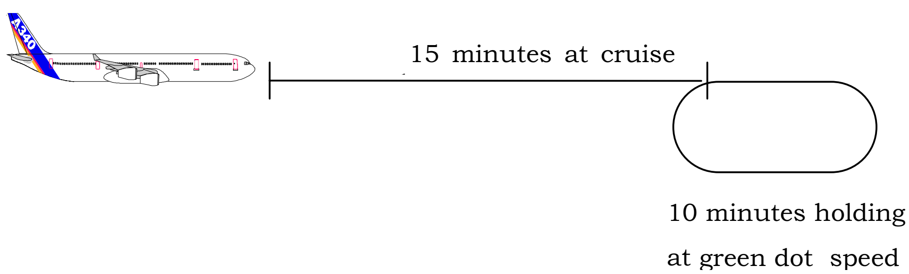
If holding is going to be necessary, linear holding at cruise flight level and at green dot speed should be performed whenever possible since total flight time will remain constant (cruise time is increased but holding time is reduced) and fuel flow is lower at high flight levels.

If A.T.C. informs 15 minutes before reaching a fix and that 10 minutes holding is expected. Two options are possible:

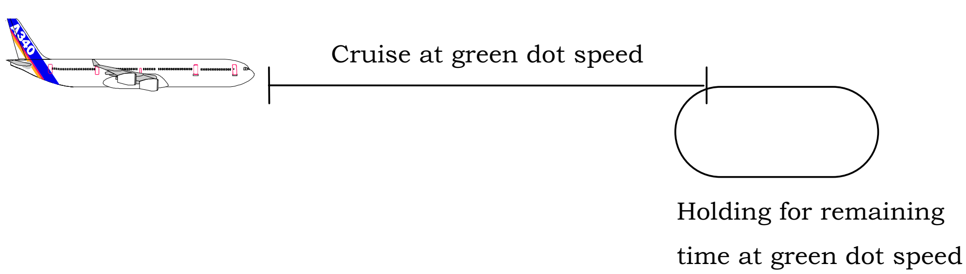
• The aircraft is flown 15 minutes at cruise speed and holds for 10 minutes at green dot speed.

• The aircraft performs the cruise to reach the fix at green dot speed and holds for the remaining time at the same speed.

Holding at cruise



Holding optimization



ATC restrictions may not permit a cruise speed reduction at the cruise flight level, or permit a hold at the cruise flight level. The standard procedure would be to continue to the top of descent at cruise speed and descend to a flight level to join the stack. However if ATC permit a linear hold it can give significant fuel savings.

However the amount of savings is very dependant on the characteristics of the aircraft type. The increase in time in the cruise depends on how much slower green dot speed is compared to the normal cruise speed. This increase was much higher with the A320 than the A340. In addition, most aircraft, flying the same cruise distance at green dot speed actually uses a little more fuel at these altitudes. The following table shows the gains due to cruising slower and spending less time in the hold at the cruise flight level.

Advantages of a 15min linear hold at cruise altitude at Green Dot speed

Aircraft type	Weight kg	Cruise Flight Level	Cruise Speed	Fuel savings kg
A300	120000	350	0.8	95
A310	110000	350	0.8	115
A318	50000	350	0.78	120
A319	50000	350	0.78	135
A320	60000	350	0.78	80
A321	70000	350	0.78	50
A330	180000	390	0.82	95
A340-200	200000	390	0.82	10
A340-300	200000	390	0.82	45
A340-500/600	270000	390	0.82	5

The high green dot speed for the A340 leads to very little advantage in linear holding. However the other aircraft show significant benefits.

If the increase in cruise time can be used to reducing the time in the holding pattern or stack, then the benefits will be similar to those shown in the table above. However the constraints of ATC are unlikely to let these benefits accrue.

5.6 APPROACH

5.6.1 FLIGHT PATH PRIOR TO GLIDE SLOPE INTERCEPTION

Procedures used in the approach phase can affect the amount of fuel consumed in this phase of the flight. The glide slope can be intercepted either horizontally between 1500ft and 2000ft or in a descending flight path above 2000ft. This latter method uses less fuel, but the amount is difficult to quantify, as it depends on the exact flight paths in each case. However, the most important feature of an approach is that it should be well executed, stabilized and safe. None of these features should be compromised in an attempt to save fuel, and the procedure flown should be that appropriate to the airport, runway, equipment, conditions, etc.

5.6.2 LANDING GEAR EXTENSION

The standard procedure is that Gear Down is selected down when Conf 2 (or flap 20 for A300/310) is achieved. The effect of extending the gear prior to this point will increase fuel burn, but the amount is difficult to quantify without knowing when the gear is extended. However, the most important feature of an approach is that it should be well executed, stabilized and safe. The use of gear is often one of the means of achieving this through speed control, and gear extension should not be delayed to save fuel.

6. DETAILED SUMMARY

6.1 INTRODUCTION

In this brochure it can be seen that there are many ways of influencing the fuel burn of an aircraft, but most depend on the way that the sector is planned and flown. Maximising the fuel economy requires:

- Good flight planning based on good data.
- Correct aircraft loading (weight and cg).
- An aerodynamically clean aircraft.
- Optimal use of systems (APU, Bleed, Flaps/Slats, Gear, etc).
- Flight Procedures using speeds and altitudes appropriate to the companies economic priorities.
- Use of the FMGS in the managed mode.
- Use of performance factors in flight planning and in the FMGS derived from an ongoing aircraft performance monitoring program.

6.2 GENERAL GUIDELINES

6.2.1 PRE-FLIGHT PROCEDURES

- For most Airbus aircraft, an aft CG position saves fuel.
- Excess weight costs fuel. Minimize zero fuel weight and embarked fuel.
- A good flight planning system will minimise fuel through correct optimisation.
- An aircraft performance measurement system and good flight planning will give confidence in fuel burn reducing extra reserve.
- Keep A.P.U. running during short turnarounds to reduce A.P.U. start cycles.
- Use ground power, when possible to save both fuel and A.P.U. life.

- Do not start engines until ready to go.
- If considered operationally acceptable, taxi with one engine out.
- Keep the aircraft in an aerodynamically clean condition.

6.2.2 TAKE-FF AND INITIAL CLIMB

- Bleeds off fuel improvements normally negated by APU fuel burn
- Lower configurations do save fuel.
- Flex thrust cost fuel but saves engine costs.
- Noise flight paths cost fuel

6.2.3 CLIMB

- Climb as close as possible to the optimum climb law.
- Fast Climb speeds use more fuel (except A340)

6.2.4 CRUISE

- The best speed for fuel burn (very low cost index) is slow and has a big time penalty.
- If possible, fly in managed mode at the cost index appropriate to the airlines economic priorities.
- Flying faster than the FMGS economical Mach number costs fuel.
- Try to fly at optimum altitude. Chase the optimum altitude.
- Flying at the cross-over altitude is faster, but costs fuel.
- Step Climb around the optimum altitude (see FCOM).
- Avoid delays in initiating a step climb.
- For short stage lengths, fly at an appropriate altitude (see FCOM).
- Wind variations with altitude can give advantages in flying at lower altitudes.

6.2.5 DESCENT

- Diminishing descent speed can allow significant fuel savings.
- Avoid early descents

6.2.6 HOLDING

- The best combination for fuel burn is clean configuration at green dot speed.
- Manoeuvrability, speed or ATC restrictions may require a hold in configuration 1 at S speed.
- If holding is to be anticipated, linear holding saves fuel.

6.2.7 APPROACH

- Avoid extending gear unnecessarily early.

6.3 FUEL SAVINGS

The following table gives examples of the savings possible through the application of correct procedures and practices. The values represent typical saving as there is variation dependant on the actual base case considered. However these figures serve to illustrate the magnitude of savings being achieved (or penalties being paid). The savings are expressed in kg of fuel for one flight, with the sector length being representative for each aircraft.

Fuel Savings Possible in the Pre-Flight phase

Item	Variation	A300	A310	A320	A330	A340-200/300	A340-500/600
Sector		2000nm	2000nm	1000nm	4000nm	6000nm	6000nm
CG	mid to aft	710	330	0	600	900	1550
Weight	-1% MTOW	380	250	100	800	1530	1920
EO Taxi	8 minutes	50	40	25	50	50	70
APU	3 min Grd Power	9	9	6	10	10	14
Ground Idle	3 min APU	18	18	9	15-24	3	9
Misrigged Slat	15mm to zero	90	90	60	270	270	270
Peeling Paint	1sq m slat to zero	12	12	8	60	60	60

Fuel Savings in the In Flight Phase

Item	Variation	A300	A310	A320	A330	A340-200/300	A340-500/600
Sector		2000nm	2000nm	1000nm	4000nm	6000nm	6000nm
TO Conf	Max to min F/S	15	15	10	24	-	50
Climb Rating	Derate 2 to full Climb	NA	NA	NA	30	120-320	445
Climb Speed	330 to 300kias	10	15	70	35	25	-10
Cruise Altitude	Optimum to –2000’	65	80	80	100	95	135
Cruise Altitude	Optimum to +2000’	90	60	25	145	30	25
Cruise Mach	Mecon+.01 to Mecon	230	430	40	330	900	2540
Delayed Climb	CFP to 500nm late	240	220	180	330	390	340
CG	mid to aft	710	330	0	600	900	1550
Descent Speed	Max to 300kt	35	40	30	70	75	100
Early Descent	CFP to 2min early	70	70	50	80	95	135
Hold	Green Dot Clean Conf	190	135	30	205	230	130

6.4 ECONOMIC BENEFITS

It may be that 5 or 10 kg extra fuel per flight does not seem significant in terms of the total fuel burn during the flight. However this saving accumulates with every flight. Sometimes the savings for an A340 seem worthwhile compared with the equivalent value for an A320, but the increased number of flight cycles for an A320 can make this saving more significant than that of the A340. The only way to assess the impact of any saving is to look at it over a given time span.

The economic impact calculations have assumed typical yearly utilisation rates, average sector lengths and sectors per year as follows:

Utilisation	A300	A310	A320	A330	A340
Flying Hours/year	2600	3200	2700	2900	4700
Average sector - nm	2000	2000	1000	4000	6000
Average flight time - hr	4.5	4.6	2.4	8.5	13.8
No of sectors/year	580	700	1125	340	340

The following table shows the annual cost savings for one aircraft associated with various fuel savings for each Airbus type based on the above utilisation figures. Fuel is assumed to cost $1/us gallon (33cents/kg).

Savings/flight	A300	A310	A320	A330	A340
10kg	$1920	$2310	$3720	$1120	$1120
50kg	$9600	$11550	$18600	$5600	$5600
250kg	$48000	$57750	$93000	$28000	$28000
1000kg	$192000	$231000	$372000	$112000	$112000

7. CONCLUSIONS

There are many factors that influence the fuel used by aircraft, and these are highlighted in this report. The unpredictability of fuel prices, together with the fact that they represent such a large burden to the airline has prompted Airbus to be innovative in the field of fuel conservation. The relationship between fuel used and flight time is such that sometimes compromise is necessary to get the best economics. Whether in the field of design engineering or in flight operations support, we have always maintained a competitive edge. Whether it is in short or ample supply, we have always considered fuel conservation a subject worth revisiting.

Fuel conservation affects many areas including flight planning, flight operations and maintenance. Airbus is willing and able to support airlines with operational support in all the appropriate disciplines. Despite the increasing efficiency of modern aircraft it is a subject that demands continuous attention and an airline that can focus on the subject, together with the Operation Support of Airbus is best placed to meet the challenges of surviving and profiting in the harsh airline environment of the 21st century.

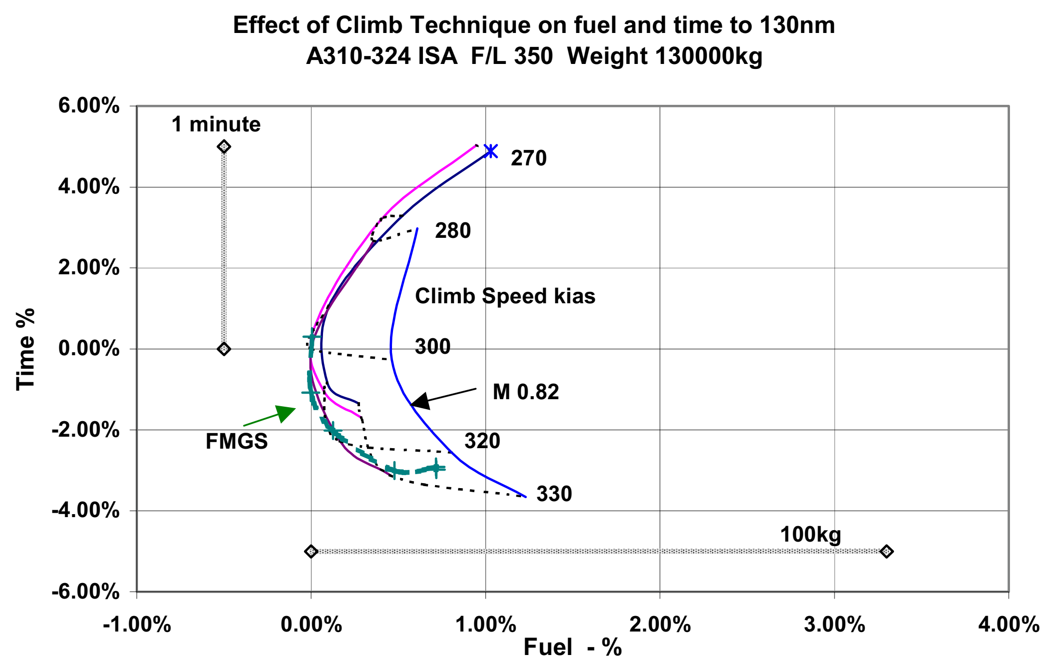
8. APPENDICES

These appendices contain climb and descent graphs for some of the other variants of Airbus aircraft. Each airframe/engine combination have different characteristics. Even the weight variant can influence these characteristics. It is therefore impossible to include all variants, but the selection shown will give an idea of the sensitivities of fuel burn and time to technique.

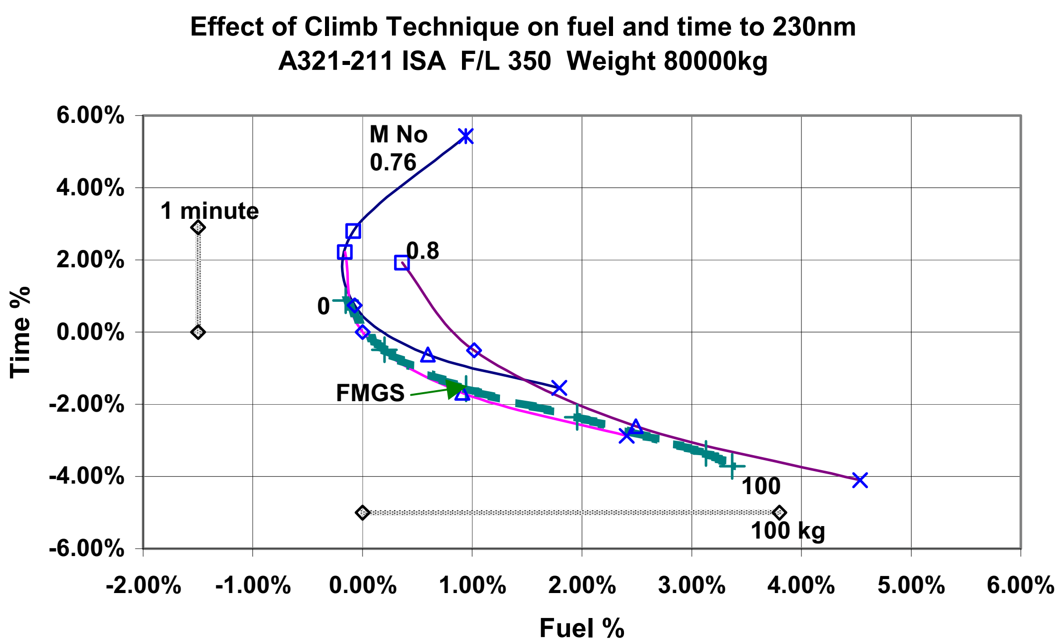
APPENDIX A (CLIMB CHARTS)

The climb chart for the A300 is given in the main report (5.2.3)

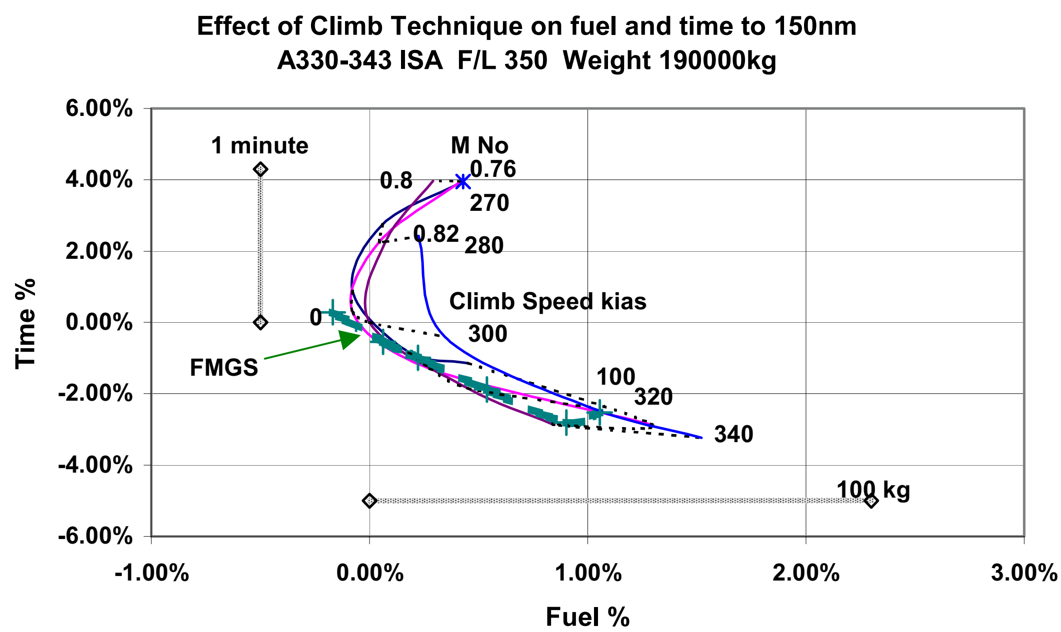
The **A310** shows similar characteristics and is shown below. Note that the lower mach numbers (0.76, 0.78 and 0.8) show no variation.



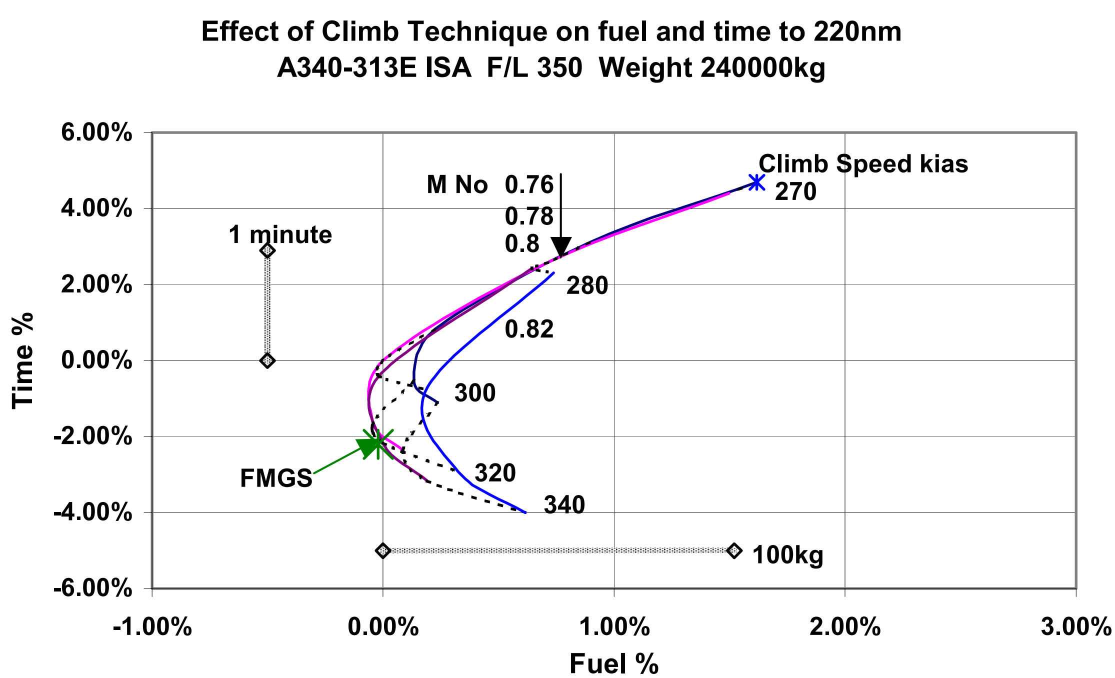
The main report gives the climb chart for the A320 which is similar to the A318 and A319. The **A321** however shows more significant differences.



The **A330** aircraft show characteristics similar to the A321 and an example is shown below.

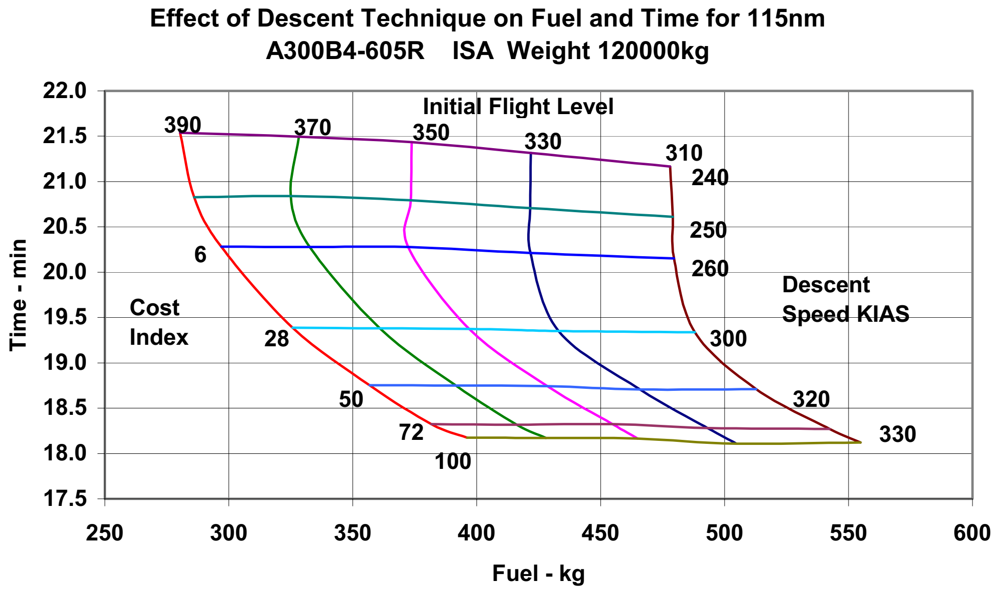


The **A340-200/300** series show characteristics approaching that of the A340-500/600 but still shows minimum fuel at a speed lower than max, unlike the A340-500/600 (see 5.2.3).

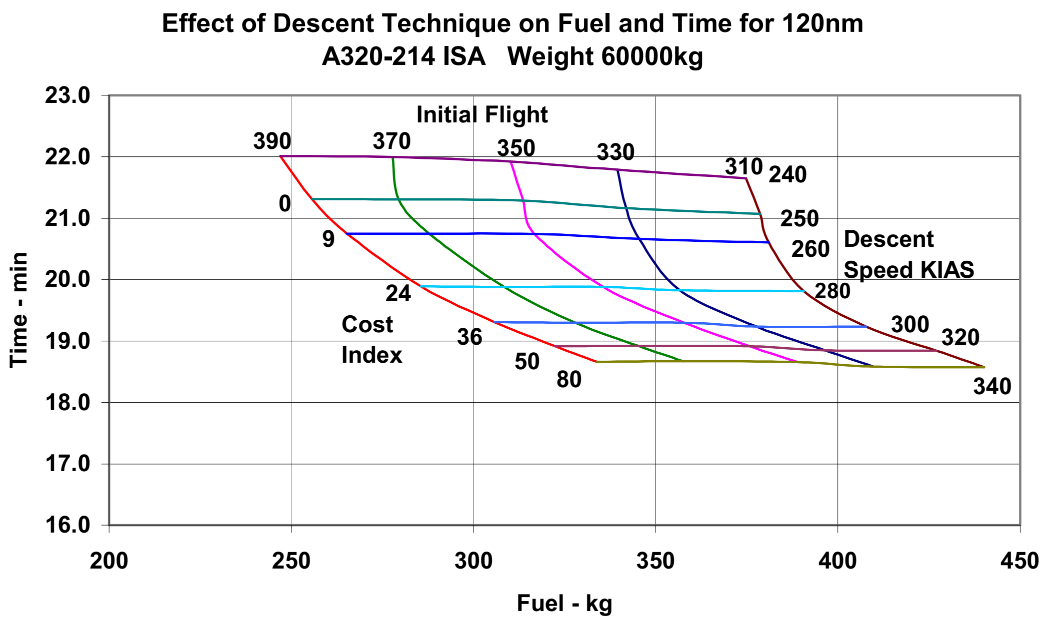


APPENDIX B (DESCENT CHARTS)

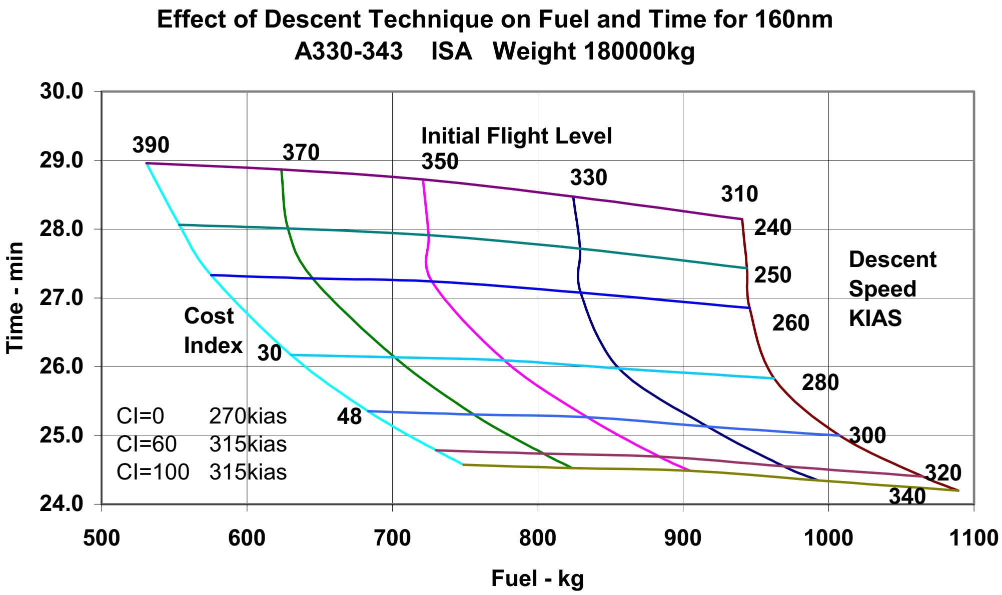
The **A300** shows similar characteristics to the A310 in the main report.



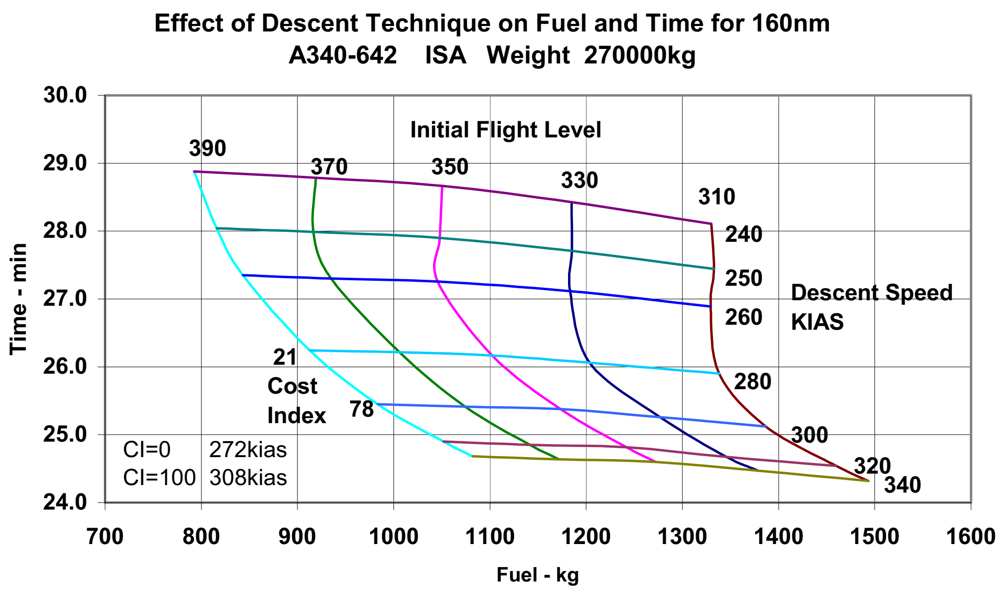
The **A320** shown below has similar characteristics to the A318, A319 and A321.



The following shows an example of an **A330**:

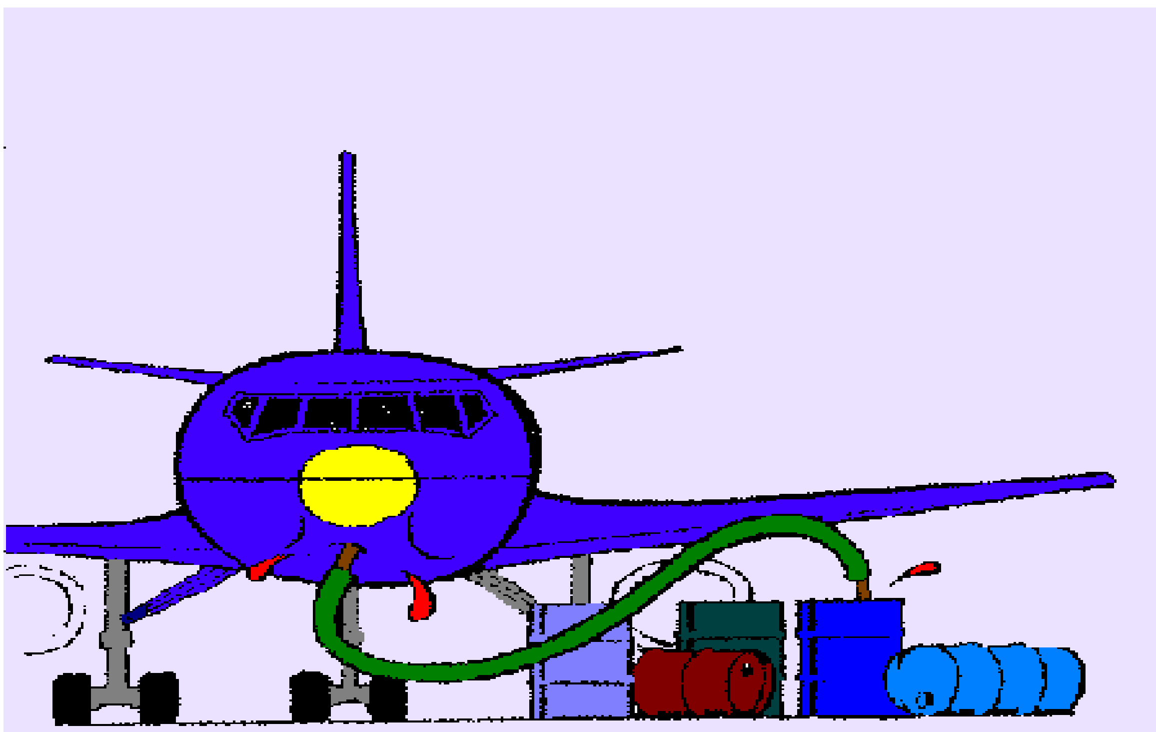


Most of the **A340**'s have similar speed characteristics to the A340-642 shown below. The A340-200 does however show an improvement in fuel for speeds lower than 260kts.



FUEL CONSERVATION
THROUGH
AIRCRAFT MAINTENANCE

This discussion on fuel conservation does not of itself bring new visions of managing aircraft maintenance. It is a review of known issues and concerns. Aircraft maintenance has been very aware of the requirements in order to manage fuel conservation. The hope is to provide a list of items relevant to the need, that may act as a catalyst in provoking some change in your operation.



- The operator must define a cost/benefit proposition, to balance savings from maintenance performance improvements, versus cost to perform maintenance.

- A defined process of Service Bulletin (SB) or Modification evaluation for voluntary incorporation of items can play a role in the cost/benefit proposition affecting fleet economics. Even the most desirable incorporation of an item can add weight to the aircraft. The overall fleet cost, for the incorporation not only of the item but the additional fuel required to manage the increased empty weight can be significant.

- Regular review of aircraft Empty Weight does pay dividends. Aircraft have been known to increase by as much as 1000 pounds in a 5 year period.

- This rationalized maintenance approach must be managed through the existing approved maintenance program. The objective being to manage a controlled process as opposed to executing random oversight over still another activity.

- Existing task cards (TC) can be revised to include the actions deemed necessary for fuel conservation activities. A key factor to using the existing TC may be the inspection interval.

- As applicable new TC can be produced to meet this criteria. To the degree possible, every attempt to utilize existing TC's is best; But guard against overloading the TC content.

- Once airline management has made the foregoing decisions they may need to resource the personnel required for aircraft down time including any other need that arises out of the increased work.

- The maintenance training program may best serve the operation by explaining to personnel the rationale behind the revision to the maintenance program.

MAINTENANCE ACTIONS

The following represent some items that may be formally introduced into the Maintenance Program or existing items that can be expanded upon ensuring the desired results. The essential component to eliminate is drag in all its forms.

- Inspect pneumatic manifolds and valves for leaks. Although many manifolds are monitored by over temperature sensing, many others are not. Even those that are monitored may be allowed to leak yet not cause a warning indication because the leak rate is too low. Over an entire aircraft however, this can be a significant loss requiring additional throttle to sustain performance.

- During approach for landing (throttled back), with the air cycle machines operative, and all pneumatic anti-icing/de-icing selected, some aircraft exhibit the need for additional power to provide the level of pneumatic demand, because of the pressure loss caused by leaks. This can also change the approach profile of the aircraft on that approach.

- Tired air cycle machines can place a demand for additional pneumatic muscle to drive them. This further adds to the need for additional fuel.

- Inspect for excessive autopilot lateral input. This can cause spoiler panel operation which induces drag consuming fuel.

- Inspect for marginal aileron rigging that will create unnecessary drag not to mention sloppy performance.

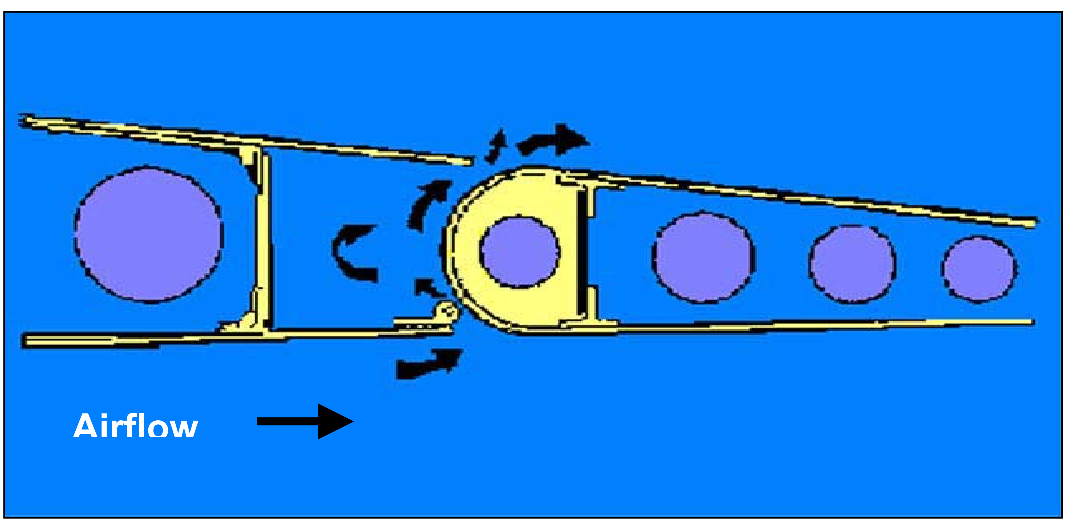
- Inspect for optimum spoiler control rigging. Spoilers are a full time control parameter; so ensuring better than nominal rigging enhances performance by not adding to the drag component.

- Ensure that wing leading edges and particularly leading edge flaps, slats and slots are not dented or damaged. Rough surfaces alone will increase drag.

- Inspect the flap system rigging for optimum position. These large surfaces are designed to manage flight regime attitudes at controlled speeds. Out of tolerance situations will cause excessive fuel burn.

- Inspect the rudder control system for optimum rig.

- Inspect all the flight controls for seal integrity. Ensure that air is directed so as to meet the intent of the design. Where applicable inspect draft curtains for condition and replace as required.



- Inspect all control surfaces for maximized fit and fair positions. Ensure correct flush fasteners are installed on all surfaces. Rough surfaces from any leaks must be corrected.

- Investigate all reported fuel quantity discrepancies, ensuring that possible problems related to contaminated probes are eliminated. Perform calibration checks for the fuel tank indication system ensuring accurate quantity readings.

- Ensure regular fuel tank sumping. Fuel tanks have experienced ice build up 4 feet in length and 18 inches to 2 feet thick. Components in these tanks may not fail immediately but may experience damage leading to calibration issues as well as structural concerns.

- Inspect tanks for algae growth and rectify as required.

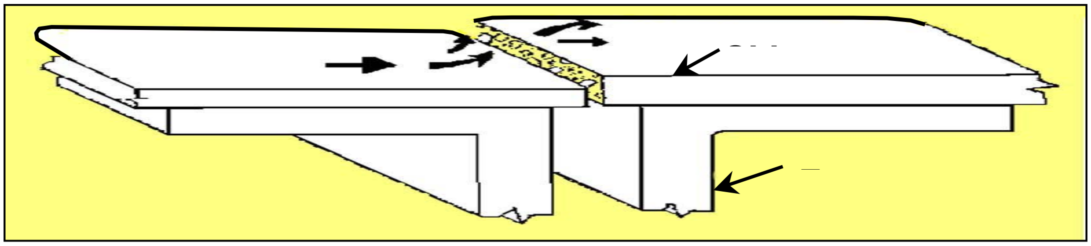
- Sump drains can allow fuel seeps or weeps. While these may be an allowable MEL dispatch criteria, over time the fuel can affect surface finish causing roughness and a resulting increase in drag.

- Inspect all areas of the aircraft for both hydraulic and fuel leaks that can degrade surface finish. Rectify leak areas and return surface finish to specification.

- Inspect pylon and other similar drain systems. Eliminate any source of leaks and ensure surface integrity of surfaces affected.

- Inspect wheel well doors for optimum fit and fair conditions. Ensure all door seals are correctly installed and in airworthy condition.

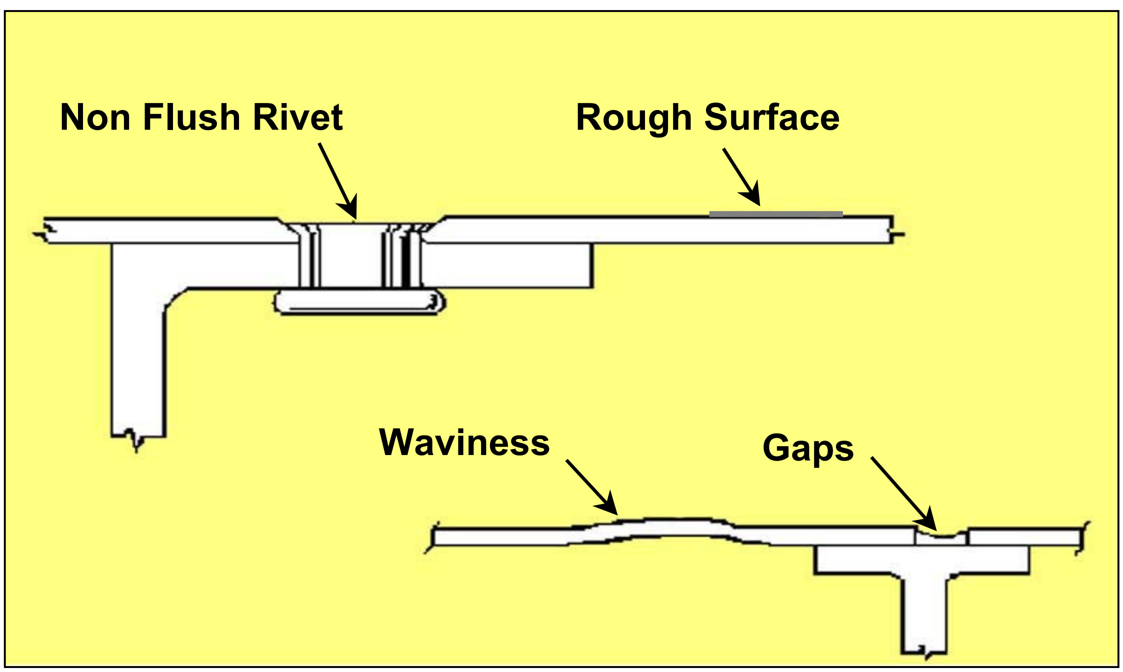
- Review pilot reports for cabin and cargo door complaints. Inspect all doors for optimum fit and fair condition. Ensure door seals integrity. Eliminate any sources of pressure leaks.



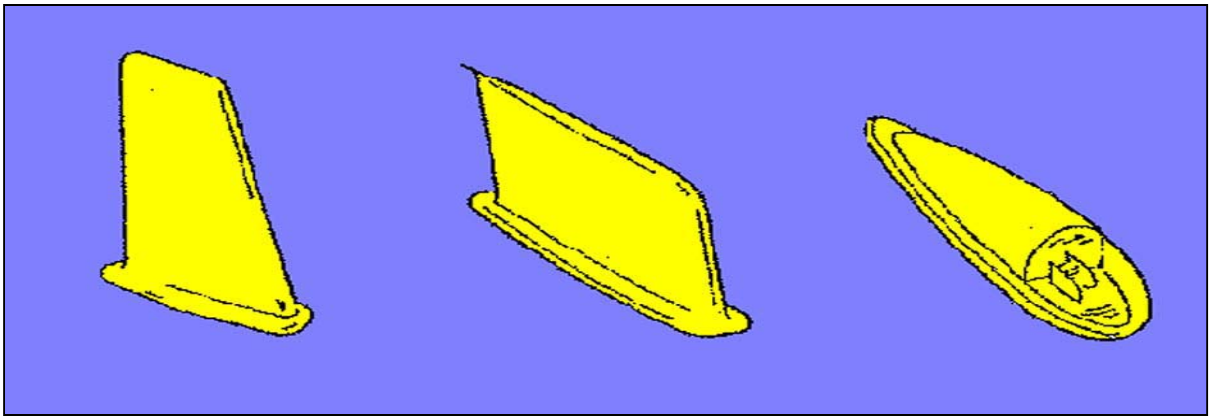
Example of typical steps at skin joints, around windows, doors, control surfaces, and access panels.

- Inspect the aircraft fuselage. All panels must be installed. The fit and fair condition ensuring smooth flow over the edges of the panel/s and mating structure must be maintained.

- Any rough surfaces must be identified and returned to a smooth condition. Any discrepancies caused by hydraulic or fuel leaks must be corrected.



- All antennae must be installed so as to maximize the best fit and fair considerations. This includes attention to the detail of sealing compound applications where required.



- A major area of air flow degradation can be the wing speed fairing/s as well as the Horizontal Stabilizer to Vertical Stabilizer fairings. Inspect these areas to ensure an enhanced installation eliminating sources of unnecessary drag.

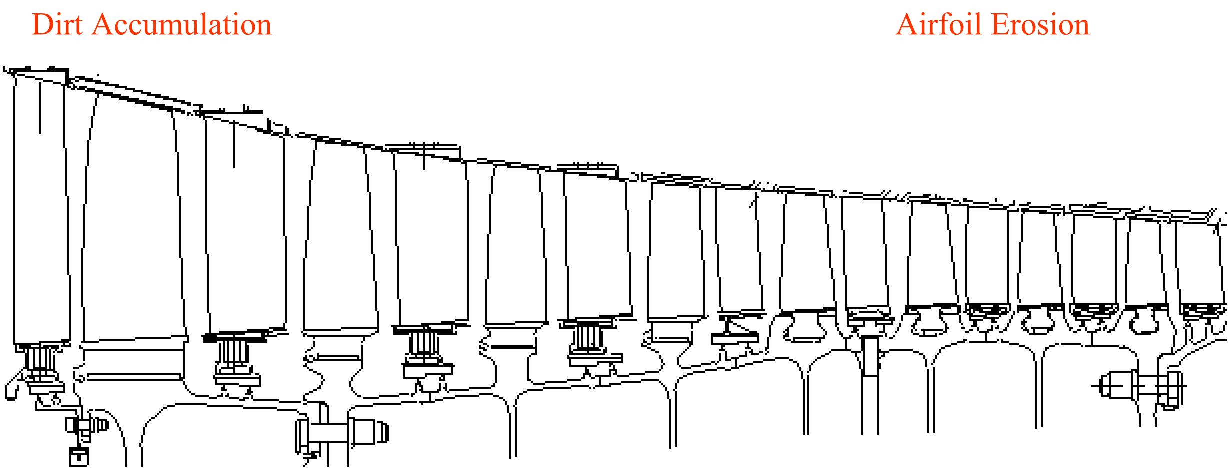
- Inspect cockpit Windscreen/s to ensure best fit and fair with the fuselage nose section structure. Any uncured sealant that may have migrated from the sealed area must be removed and the surface area cleaned.

- Inspect engine and thrust reverser translating cowls for correctly stowed fit clearances.

- The following items cause fuel burn deterioration:

  - Blade rubs – HP Compressor, HP Turbine, airfoil blade erosion.
  - Thermal distortion of blade parts.
  - Blade leading edge wear.

- Excessive fan rub strip wear.
- Lining loss in the HP Compressor.
- Oil or dirt contamination of LP/HP compressor.



- Loss of High Pressure Turbine (HPT) outer air seal material.
- Leaking thrust reverser seals.
- ECS leaks
- Failed – open fan air valves
- Failed – open IDG air cooler valves.
- Faulty turbine case cooling
- Failed or faulty 11th stage cooling valves.

- On wing engine washing can address dirt accumulation with the compressor. Leakage caused by the bleed air system can be remedied by on wing engine bleed rigging and additionally provide up to 2.5% Specific Fuel Consumption (SFC) benefit. Regular on – wing engine washing can bring as much as a 1.5% SFC improvement.

- An aircraft wash and polish program can produce clean smooth airflows over the surfaces enhancing fuel burn figures.

- Ensure regular Instrument Calibration checks. Speed measuring equipment has a large impact on fuel mileage. If speed is not accurate the airplane may be flying faster or slower than intended. On a particular commercial transport flying at .01M faster can increase fuel burn by 1% or more. Maintain calibration of airspeed systems. Plugging or deforming the holes in the alternate static port can result in erroneous instrument readings in the flight deck. Keeping the circled area smooth and clean promotes aerodynamic efficiency. Maintenance operations must ensure the use of proper tooling to block the static ports. Check the Illustrated Tool and Equipment List (ITEL) for the applicable aircraft model

Estimated Fuel Savings

Example of an estimated fuel penalty in liters per year, per aircraft, for a 5 millimeter surface mismatch.

Passenger front door	9000
Nose Landing Gear Door	8400
Cargo Door - Forward	8800

Example of an estimated fuel penalty in liters per year, per aircraft, per each 5 centimeters of missing door seals.

Item	Sides	Top/Bottom
Passenger Front Door	1500	800
Cargo Door	1500	800

Example of an estimated fuel penalty in liters per year, per aircraft, for control surface misrigging of 10 millimeters..

Slat	28000
Flap	10000
Spoiler	32000
Aileron	10000
Rudder	13000

Examples of the estimated penalty in liters per aircraft per year for single dents or blisters.

Item	Surface Area Damaged	5 MM Depth
Fuselage	20 Square Cm.	70
	80 Square Cm.	270
Wing	20 Square Cm.	85
	80 Square Cm.	370
Tail	20 Square Cm.	45
	80 Square Cm.	90

Examples of estimated fuel penalty in liters per year, per aircraft for 0.3 mm of skin roughness over 1 square meter.

Area	Penalty
Fuselage	3300
Wing Skin (upper)	12000
Wing Skin (lower)	6000
Tail	5800

Examples of estimated fuel penalty in liters for parts missing.

Type of Deterioration	Penalty in Liters /Year
Absence of seal on movable surface	Per meter of missing seal
Slats (span wise seal)	14000
Flaps & Ailerons (chord-wise seal)	9500
Elevator	6300

Engine Cowl: One pressure relief door missing	134000
Cargo Door: Lock cover plate missing)	1000
Fin/Fuselage junction (fairing & seal missing)	39500
Elevator bearing access cover missing	19000

Conclusions

The double outcome of this drag component is not only the added cost of fuel to overcome it but also the lost payload. On a typical commercial transport it is conceivable, that in order to offset a 1% increase in drag, a reduction in Zero Fuel Weight (ZFW) could be 260 pounds/118 kilograms, in order to maintain a constant takeoff weight. (Note that the reductions vary as actual values vary with distance flown. Also the above figure varies up or down depending on the actual aircraft in question). Considering the example provided above, a 1% drag in terms of gallons per year could result in approximately 25000 gallons.

Any one item on this list may of itself bring miniscule benefit. However, in combination the savings can be substantial per aircraft. Exponentially applying these figures to an operators fleet brings large returns.

Sources of additional information are:

- Operational Opportunities to Minimize Fuel Use and Reduce Emissions. (ICAO Circular 303, AN/176).
- Fuel Conservation & Maintenance Practices for Fuel Conservation / Boeing Commercial Airplanes
- Operational Expertise Documentation / Airbus Customer Services
- Engine Manufacturers / Customer Support Departments.

Fuel Conservation
Airframe Maintenance for Environmental Performance

Dave Anderson
Flight Operations Engineering
Boeing Commercial Airplanes
September 2006

Maintenance Personnel

Opportunities For Fuel Conservation

- Empty weight control
- Airframe maintenance
- Systems maintenance

Reducing Aircraft Weight Reduces Fuel Burned

Approximate %Block Fuel Savings Per
453 kg (1000 lb) ZFW Reduction

717-200	737-3/4/500	737-6/7/8/900	757-200/300	767-2/3/400	777-200/300	747-400
.9%	.7%	.6%	.5%	.3%	.2%	.2%

Reducing OEW Reduces ZFW

Items To Consider

- Passenger service items
- Passenger entertainment items
- Empty Cargo and baggage containers
- Unneeded Emergency equipment
- Excess Potable water



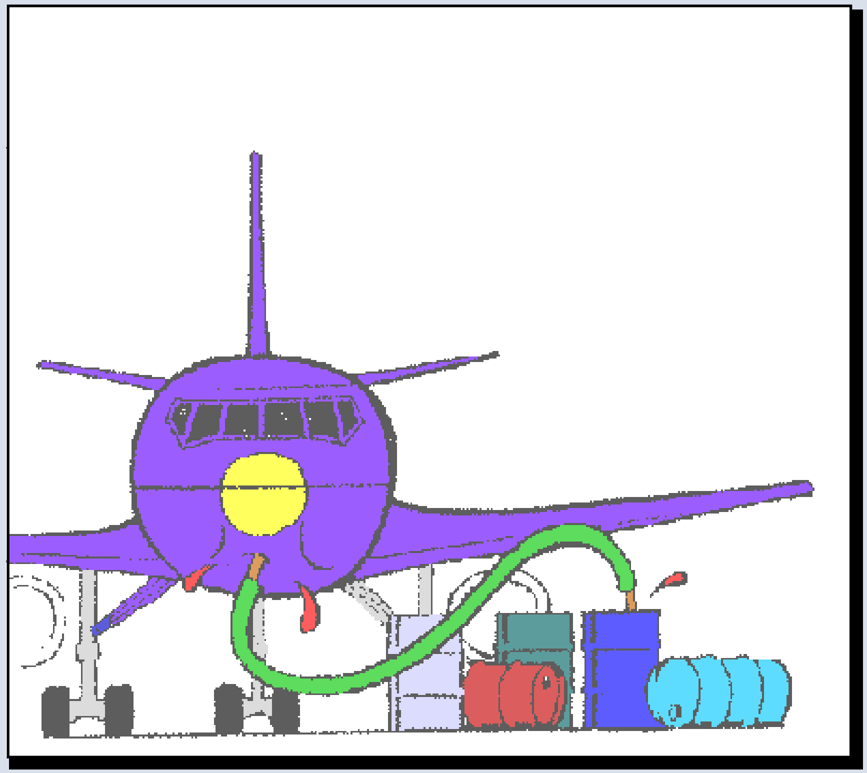
Reducing OEW Reduces ZFW

- Operating empty weight (OEW) increases on average 0.1% to 0.2% per year, leveling off around 1% after 5 to 10 years
- Most OEW growth is mainly due to moisture and dirt

Reducing Aircraft Drag Reduces Fuel Burned

Effect of a 1% Drag Increase In Terms Of Gallons Per Year

- 747 ≈ 100,000
- 777 ≈ 70,000
- 767 ≈ 30,000
- 757 ≈ 25,000
- 737 ≈ 15,000
- 727 ≈ 30,000



(Assumes typical aircraft utilization rates)

Total Drag Is Composed Of:

Compressible drag ≈ drag due to high Mach

- Shock waves, separated flow

Induced (vortex) drag ≈ drag due to lift

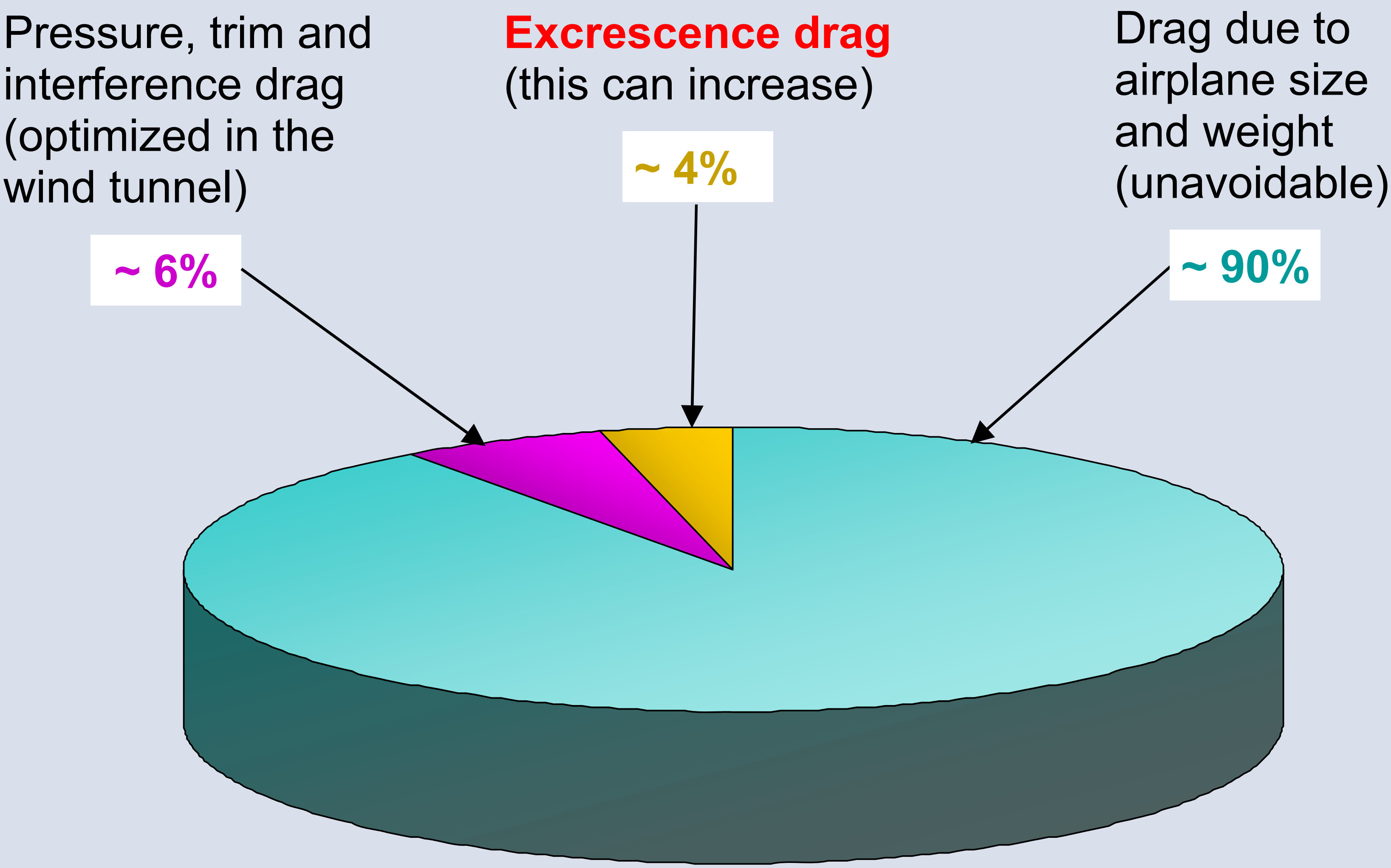
- Downwash behind wing, trim drag

Parasite drag ≈ drag **not** due to lift

- Shape of the body, skin friction, leakage, interference between components
- Parasite drag **includes** **excrescence** drag

Contributors To Total Airplane Drag

(For a new airplane at cruise conditions)



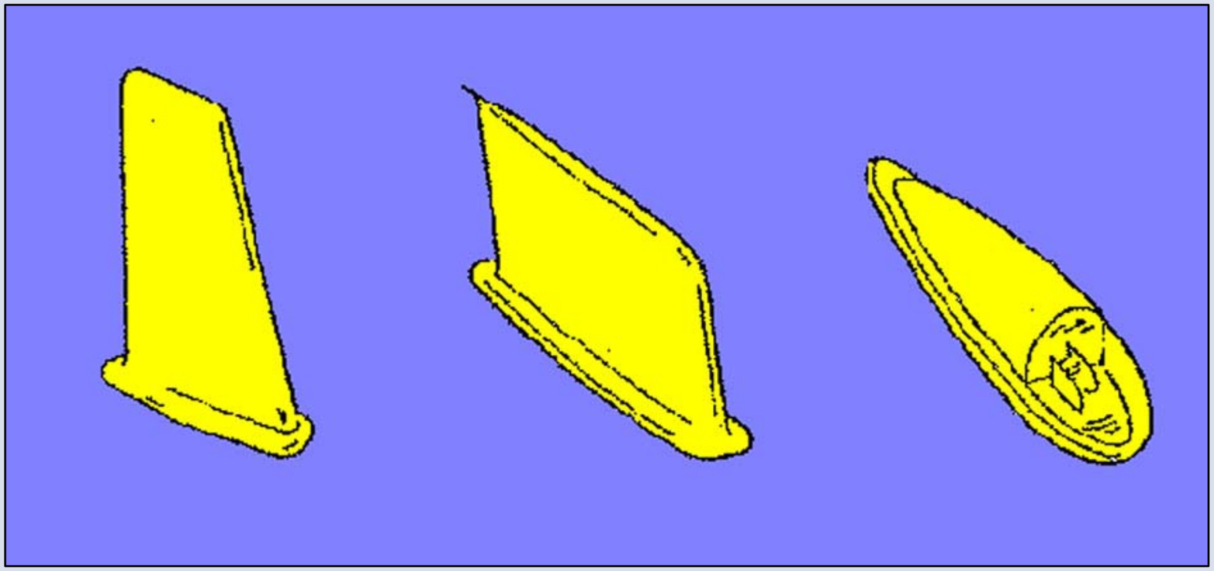
What Is Excrescence Drag?

The additional drag on the airplane due to the sum of all deviations from a smooth sealed external surface

Proper maintenance can prevent an increase in excrescence drag

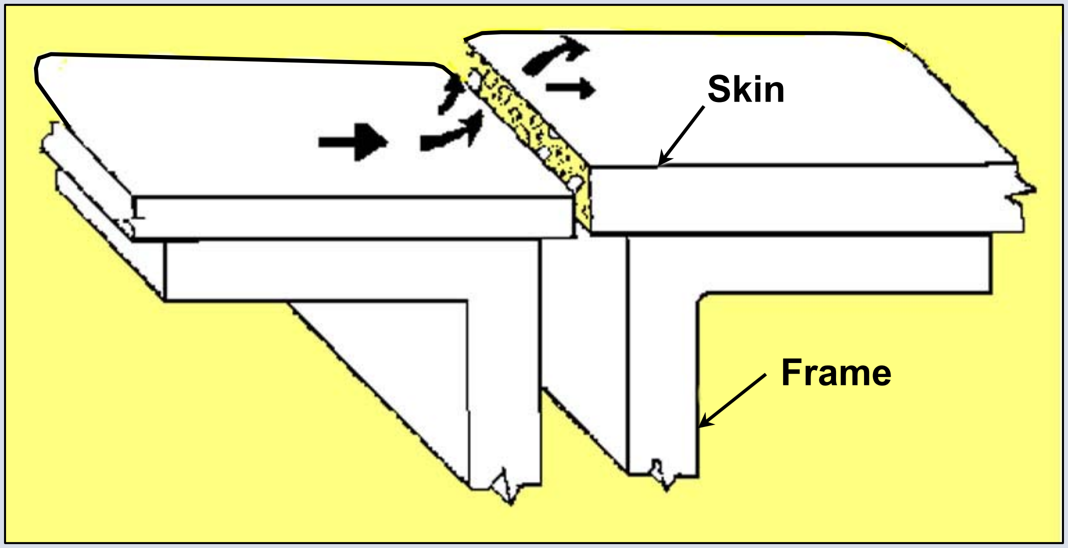
Discrete Items

- Antennas, masts, lights
- Drag is a function of design, size, position

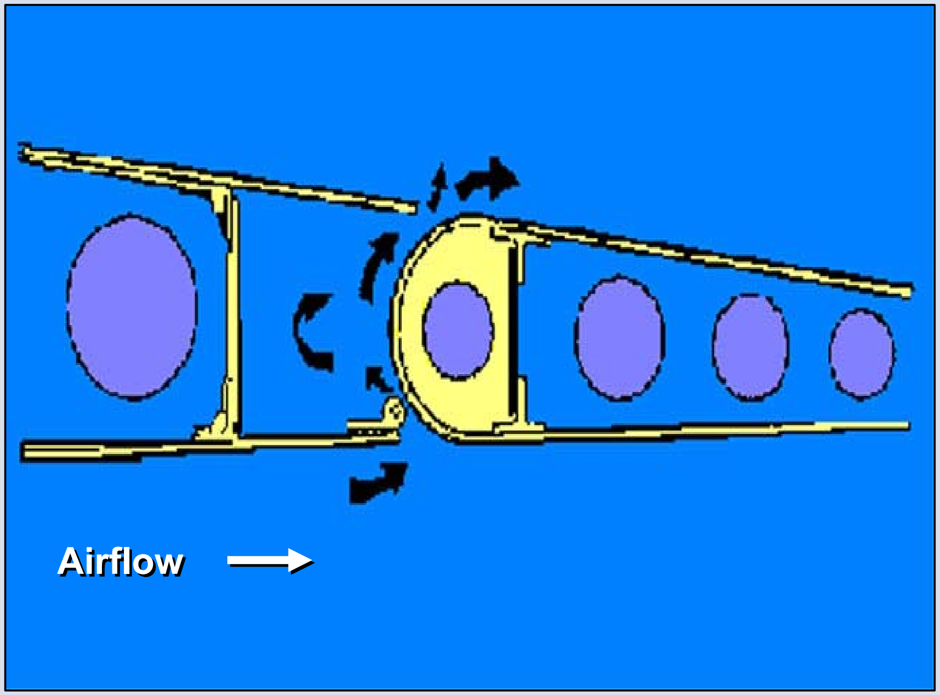


Mismatched Surfaces and Gaps

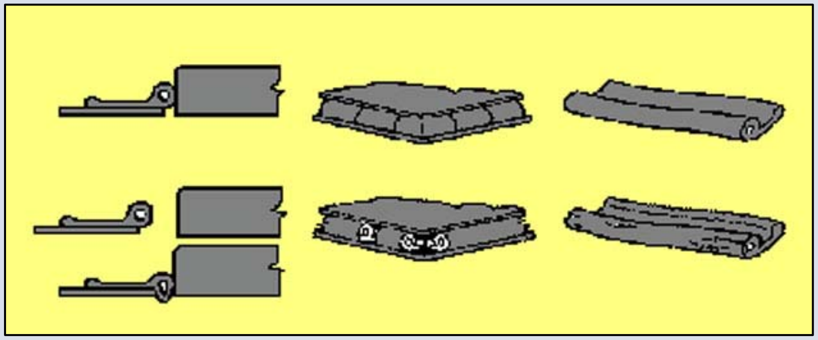
Steps at skin joints, around windows, doors, control surfaces, and access panels



Internal Airflow

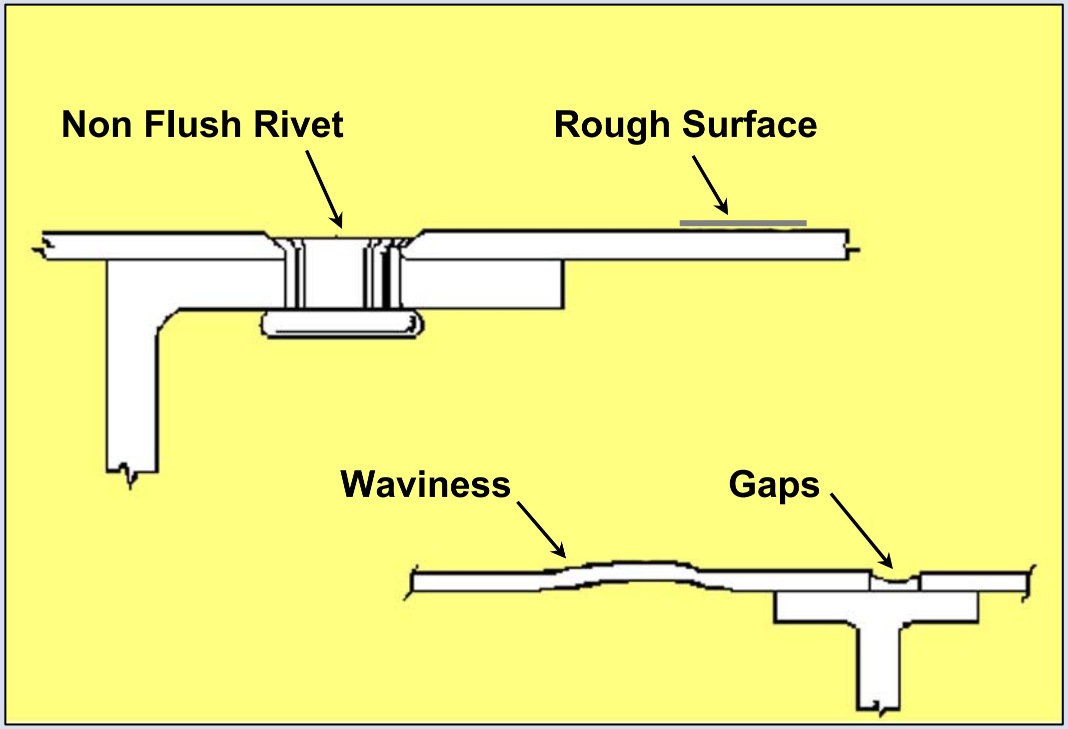


Leaks through gaps, holes, and aerodynamic seals



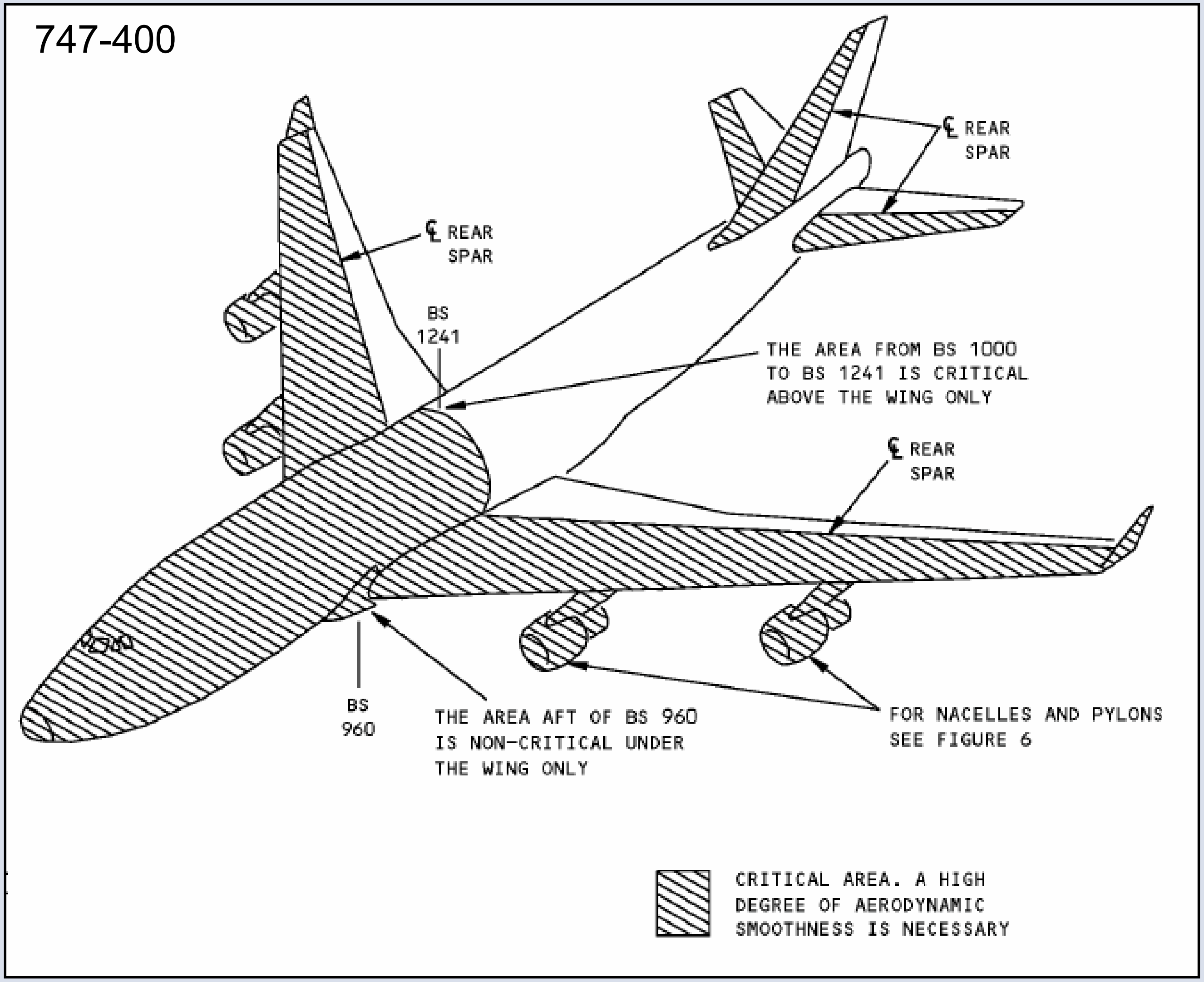
Roughness
(Particularly Bad Near Static Sources)

- Non-flush fasteners, rough surface
- Waviness, gaps



Most Important in Critical Areas

- Structural Repair Manuals Identifies Critical Areas



Average Results Of In-service Drag Inspections

Average total airframe drag deterioration ~ 0.65%, composed mainly of:

- Control Surface Rigging ≈ 0.25%
- Deteriorated Seals ≈ 0.20%
- Misfairs ≈ 0.1%
- Roughness ≈ 0.05%
- Other ≈ 0.05%

A well-maintained airplane should not exceed 0.5% drag increase from its new airplane level

Regular Maintenance Minimizes Airframe Deterioration

- Flight control rigging
- Misalignments, mismatches and gaps
- Aerodynamic seals
- Empty weight control
- Exterior surface finish
- Instrument calibration/maintenance

Maintain a Clean Airplane

- Maintain surface finish
- Fluid leaks contribute to drag
- Periodic washing of exterior is beneficial
  - 0.1% drag reduction if excessively dirty
  - Minimizes metal corrosion and paint damage
  - Location of leaks and local damage
- Customer aesthetics

Instrument Calibration/Maintenance

- Speed measuring equipment has a large impact on fuel mileage - keep airspeed system maintained
- If speed is not accurate then aircraft is flying faster or slower than intended - airspeed reads 1% low, aircraft flying 1% fast
- On the 747-400, flying 0.01M faster then intended can increase fuel burn by over 1%

Proper and Continuous Airframe and Engine Maintenance Will Keep Aircraft Performing at Their Best!

Conclusions

It Takes the Whole Team to Win

- Large fuel (and emissions) savings results from the accumulation many smaller fuel-saving actions and policies
- Dispatch, flight operations, flight crews, **maintenance**, management, all need to contribute

Thank You!

FLIGHT
OPERATIONS
ENGINEERING

End of Fuel Conservation

Airframe Maintenance for Environmental Performance

Dave Anderson
Flight Operations Engineering
Boeing Commercial Airplanes
September 2006

Maintaining for Fuel Efficiency

Oct 26, 2006

By Robert A. Searles

The days of cheap Jet A are long gone, so airlines continue to seek ways to reduce their fuel bills. Most carriers already carefully monitor aircraft fuel performance and fine-tune routings, dispatch and operating procedures to be more efficient. However, a number of airlines also have discovered that implementing certain aircraft and engine maintenance practices and product improvements can produce substantial fuel savings.

The American Experience

Ever since 737-800 Captain Steve Chealander was named manager of flight operations efficiency at American Airlines more than three years ago, he has been trying to find ways to make the carrier more fuel-efficient without compromising safety. American, like a growing number of airlines, has installed winglets on some aircraft to conserve fuel, but the carrier keeps a close eye on the fuel efficiency of all of its airplanes.

"We are finding some aircraft with lower-than-book-value fuel efficiency," noted Chealander, and the maintenance department is asked to determine why these airplanes are underperforming. "There are a lot of adjustments that can be made -- how the airplane is trimmed, whether the ailerons are perfectly aligned. We are very conscious of that. So we tune them up. There is a lot of money [to be saved] in [doing] that."

American Airlines also is engaged in a comprehensive aircraft weight-reduction program. Ovens and galleys have been removed from aircraft on which hot food is not served. The airline also carries less potable water on flights. Maint- tenance personnel used to simply fill the water tanks prior to flight, but a study revealed that usually less than half the water was being consumed. Rather than change the water-tank filling procedure, the maintenance department designed a $1 valve that shuts off the filler hose when the tank reaches 75 percent capacity, which reduces aircraft weight by about 100 pounds and saves approximately $2.8 million in fuel annually.

American also has set up an engine wash program to remove debris and carbon deposits from powerplants, which allows them to run more efficiently and burn less fuel. That program saves about four million gallons of fuel per year. The carrier has found ways to burn less kerosene on the ground. Instead of running the auxiliary power unit (APU) while an aircraft is in for maintenance, technicians plug the airplane into ground power or preconditioned air units. And American is beginning to use high-speed tractor tugs to move airplanes into the maintenance hangar so that engines are not used to taxi the aircraft.

American also has examined each aircraft's minimum equipment list (MEL) and found that flying with certain inoperative items can have a big impact on fuel consumption. For example, if the automatic start switch for the Boeing 777's APU is not working, the APU must run during the entire flight. "Imagine if we've got an APU running from DFW to Tokyo, how much money that would cost at $4 a minute," said Chealander.

To prioritize the repair of MEL-related items, each day American mechanics identify all fuel-related items and assign them either a red, yellow or green light designation. "If it's a red light, it's a high priority fix," said Chealander.

Efforts at Alaska and Hawaiian

Alaska Airlines has adopted many of the same fuel-savings measures that American and other carriers have implemented, but Alaska recently had an outside auditor check to see if the airline could do more, said Scott Ridge, managing director of technical operations and support. "The audit revealed that we were pretty much doing everything that manufacturers recommended [in terms of maintenance]," said Ridge. However, the auditor suggested performing engine washes with hot water instead of cold to make them more effective.

Alaska also is considering certain fuel- and weight-saving product improvements. The carrier plans to have CFM56 engine-performance improvement kits installed on its 737s, and the airline is considering putting carbon brakes on those planes, which would save almost 800 pounds.

"This [fuel conservation effort] is something that is really important to us," said Ridge. "We are going to continue to put a lot of emphasis on it. The cumulative effects are very important because these are not one-time savings. We are leaving no stone unturned, from big ones, like winglets, which are saving $150,000 per year, to the [small] ones that are going to save us $10,000 per year."

Meanwhile, Yesso Joseph Tekerian, senior director of engineering at Hawaiian Airlines, said, "Engine washing and re-rigging control surfaces are the two most expedient maintenance practices that we know of. It is conceivable that we could tighten limits on body-to-wing fairing seals and landing gear door seals, but there are no data to substantiate any credible gains."

Control surface re-rigging of Hawaiian's airplanes are done during C checks, and the Pratt & Whitney PW4000 engines that power the carrier's 767s are washed twice a year by the engine maker. Hawaiian washes the BR715 engines on its 717s four times a year.

Tools from Boeing

While most airlines have devised their own fuel savings measures, they also seek input from aircraft and engine manufacturers and third-party MRO providers. Many carriers have turned to Boeing for advice.

Rob Root, a Boeing flight operations engineer, said the key to maximizing fuel efficiency is to minimize increases in aircraft drag, especially those associated with control surfaces that are out of rig and aerodynamic seals that are leaking. He also recommends that operators look closely at gaps between fairings and external panels. Bad door seals impose a double penalty because the air conditioning system has to work harder, and leaking air can disrupt airflow around the airplane and increase drag.

In the final analysis, however, only a small part of fuel inefficiency can be attributed to the airframe. Most is caused by the way the engines are operated. For example, use of higher takeoff thrust can cause the fuel mileage of engines to deteriorate more rapidly. Conversely, using reduced takeoff thrust can save fuel.

Operating practices and maintenance procedures often impact each other. "It is very important to fly at the right speed to get the best fuel mileage," said Root. "But that has a corollary on the maintenance side: If the airspeed system is not properly maintained, the airspeed the pilot is seeing is actually different [higher] than what he thinks he is flying. That could result in a fuel penalty." Therefore, it is important to maintain the static port to prevent erroneous airspeed readings.

Some operators are convinced that removing exterior paint is an excellent cost-savings move. It does reduce weight, "but Boeing believes that it is probably offset by the increase in maintenance costs associated with having to maintain an unpainted airplane," said Root. "There are a few operators that do it because they feel that their livery is a product differentiator, but I don't think they can justify it in economic terms." However, Root added, "loose or peeling paint can have a fairly significant impact on fuel mileage."

All told, Boeing has amassed nearly 40 years of data on fuel consumption, and the manufacturer can provide to operators, free of charge, several fuel-conservation resources.

Because aircraft fuel burn varies substantially by carrier, Boeing provides a software tool called Airplane Performance Monitoring, which allows operators to analyze their fuel consumption. Sometimes the results of such trend monitoring indicate that one aircraft burns more fuel than the others. That might prompt a maintenance department to inspect the airplane to see if there is an obvious reason for the deviation.

Another Boeing resource is a document titled Airplane Maintenance for Fuel Conservation, which quantifies the fuel penalties associated with various out-of-tolerance situations in terms of gallons per year based on average aircraft utilization by aircraft model. The publication also estimates the number of maintenance man-hours needed to correct those conditions. Armed with that information, operators can judge for themselves which items are worth fixing.

Tips from MRO Providers

Andreas Pakszies, director of aircraft system engineering at Lufthansa Technik, advocates using a variety of measures to improve aircraft fuel efficiency. One of the engine adjustments that can be made on non-FADEC powerplants is a variable stator vane optimum rig, which can reduce engine fuel consumption up to 0.5 percent.

Lufthansa Technik also "dry washes" some airplanes, which involves applying a special polishing powder to the exterior rather than washing it. It is believed that the smoothness of the dry wash finish has a positive influence on fuel consumption.

Mickey Cohen, vice president of operations and engineering for AAR, said that his people always are on the lookout for maintenance issues that could affect fuel consumption. "We tell our inspectors to pay particular attention to misalignment of body panels, doors and closure panels. If a door is inset up to a quarter inch, it could function properly and there would be no airworthiness issues, but it would cause additional fuel burn because of additional drag."

Cohen said that jetliners tend to gain up to 150 pounds of weight because of accumulating moisture, dust and dirt. He suggested that operators periodically clean out the wheel wells and other nooks and crannies of airplanes. "With fuel at the price that it's at, you look at everything you can," he said.

Achieving optimum fuel savings requires cooperation between aircraft manufacturers, airlines and MRO providers, but the efforts clearly are worthwhile. "A lot of these programs seem small," said American's Chealander. "But when you add them up, you can save millions of gallons [of fuel] just by being conscientious about the little things." In 2005, American saved 84 million gallons, and this year the carrier expects to save close to 100 million. At more than $2 a gallon, those are impressive savings indeed.

This article appeared in Overhaul & Maintenance's *October 2006 issue.*

getting to grips with

fuel economy

Issue 3 - July 2004

Customer Services

AIRBUS

Flight Operations Support & Line Assistance

Customer Services
1, rond-point Maurice Bellonte, BP 33
31707 BLAGNAC Cedex FRANCE
Telephone (+33) 5 61 93 33 33
Telefax (+33) 5 61 93 29 68
Telex AIRBU 530526F
SITA TLSBI7X

getting to grips with

fuel economy

Issue 3 - July 2004

AIRBUS

TABLE OF CONTENTS

1. SUMMARY

Fuel Consumption is a major cost to any airline, and airlines need to focus their attention on this in order to maintain their profitability. This brochure looks at all the significant operating variables that affect fuel economy for the current Airbus range of aircraft.

This brochure shows that there are many factors that affect fuel consumption and that the potential gains and losses are huge. Most of these factors are directly controlled by the airlines own employees (flight crew, operations/dispatch, maintenance, etc.).

It can be also seen that what is good for one type of aircraft is not necessarily good for another, and that certain conceptions regarding best techniques for fuel economy are wrong.

Finally for a fuel and cost economic airline, the following are the main features:

- Good flight planning based on good data.
- Correct aircraft loading (fuel weight and CG).
- An aerodynamically clean aircraft.
- Optimal use of systems (APU, Bleed, Flaps/Slats, Gear, etc).
- Flight Procedures using speeds and altitudes appropriate to the companies economic priorities.
- Use of the FMGS in the managed mode.
- Use of performance factors in flight planning and in the FMGS derived from an ongoing aircraft performance monitoring program.

2. PREAMBLE

The very competitive and deregulated aviation market as well as the fear of a fuel price rise have made airlines understand how important it is to work on the fuel consumption of their fleet. Indeed airlines try to reduce their operational costs in every facet of their business, and fuel conservation has become one of the major preoccupations for all airlines, as well as aircraft manufacturers. That's why all ways and means to reduce fuel costs have to be envisaged, safety being of course the number one priority in any airline operation.

The purpose of this document is to examine the influence of flight operations on fuel conservation with a view towards providing recommendations to enhance fuel economy.

It is very rare that the reduction of fuel used is the sole priority of an airline. Such instances are to maximize range for a given payload, or to decrease fuel uplift from a high fuel cost airport. Generally fuel is considered one of the direct operating costs and an airline tries to minimize total direct operating costs. This introduces the concept of Cost Index and is the scope of another brochure (Getting to Grips with the Cost Index). However it is sometimes necessary to consider the cost implication of a fuel economy, and this is done where necessary in this brochure.

This brochure systematically reviews fuel conservation aspects relative to ground and flight performance. Whilst the former considers center of gravity position, excess weight, flight planning, auxiliary power unit (A.P.U.) operations and taxiing, the latter details climb, step climb, cruise, descent, holding and approach.

None of the information contained herein is intended to replace procedures or recommendations contained in the Flight Crew Operating Manuals (FCOM), but rather to highlight the areas where maintenance, operations and flight crews can contribute significantly to fuel savings.

3. INTRODUCTION

This brochure considers the two flight management modes: "**managed**" mode and "**selected**" mode.

The **managed mode** corresponds to flight management by means of a dedicated tool, the flight management system (FMS). Crews interface through the multipurpose control and display unit (MCDU) introducing basic flight variables such as weight, temperature, altitude, winds, and the cost index. From these data, the FMS computes the various flight control parameters such as the climb law, step climbs, economic Mach number, optimum altitude, descent law. Hence, when activated, this mode enables almost automatic flight management.

When in managed mode, aircraft performance data is extracted from the FMS database. This database is simplified to alleviate computation density and calculation operations in the FMS, but individual aircraft performance factors can produce good correlation with actual aircraft fuel burns.

When in **selected mode**, crews conduct the flight and flight parameters such as speed, altitude, and heading have to be manually introduced on the flight control unit (FCU).

The **cost index (CI)** used in the managed mode provides a flexible tool to control fuel burn and trip time to get the best overall economics. A technique that reduces fuel burn often requires more trip time. Hence fuel savings are offset by time related costs (hourly maintenance costs, flight and cabin crew costs and marginal depreciation or leasing costs). The cost index is the cost of time ($/min) compared with the cost of fuel ($/kg) and is used to obtain the best economics.

If fuel costs were the overriding priority, because fuel costs were much more significant than the cost of time, then the cost index would be low. With zero cost of time it would be zero and the FMS would fly the aircraft at Mach for max range (MMR).

However if the cost of fuel was very cheap compared to the cost of time, then speed would be important and the CI would be high. For zero cost of fuel, the Cost Index would be 999 and the FMS would fly the aircraft just below MMO.

Best economics would be between these two speeds and would depend on the operator's cost structure and operating priorities. For more information on Cost Index see "Getting to Grips with the Cost Index"



4. PRE-FLIGHT PROCEDURES

Operation of the aircraft starts with the aircraft on the ground by aircraft maintenance, preparation and loading.

This part intends to highlight the impact of some ground operations on fuel consumption. Even if these operations enable only little savings in comparison with savings made during the cruise phase, ground staff has to be sensitive to them and should get into good habits.

This part is divided into seven different sections:

- Center of gravity position
- Excess Takeoff weight
- Flight Planning
- Ways of taxiing to save fuel
- Auxiliary Power Unit
- Fuel Tankering
- Aerodynamic Deterioration

4.1 CENTER OF GRAVITY POSITION

4.1.1 INTRODUCTION

The gross weight is the sum of the dry operating weight, payload and fuel and acts as one force through the center of gravity (CG) of the aircraft. The balance chart allows the determination of the overall center of gravity of the airplane taking into account the center of gravity of the empty aircraft, the fuel distribution and the payload. It must be ensured that the center of gravity is within the allowable range referred to as the center of gravity envelope.

A more forward center of gravity requires a nose up pitching moment obtained through reduced tail plane lift, which is compensated for by more wing lift. This creates more induced drag and leads to an increase in fuel consumption. It is better to have the center of gravity as far aft as possible. As a rearward shift in CG position deteriorates the dynamic stability of the aircraft, the CG envelope defines an aft limit.

4.1.2 AUTOMATIC CENTER OF GRAVITY MANAGEMENT

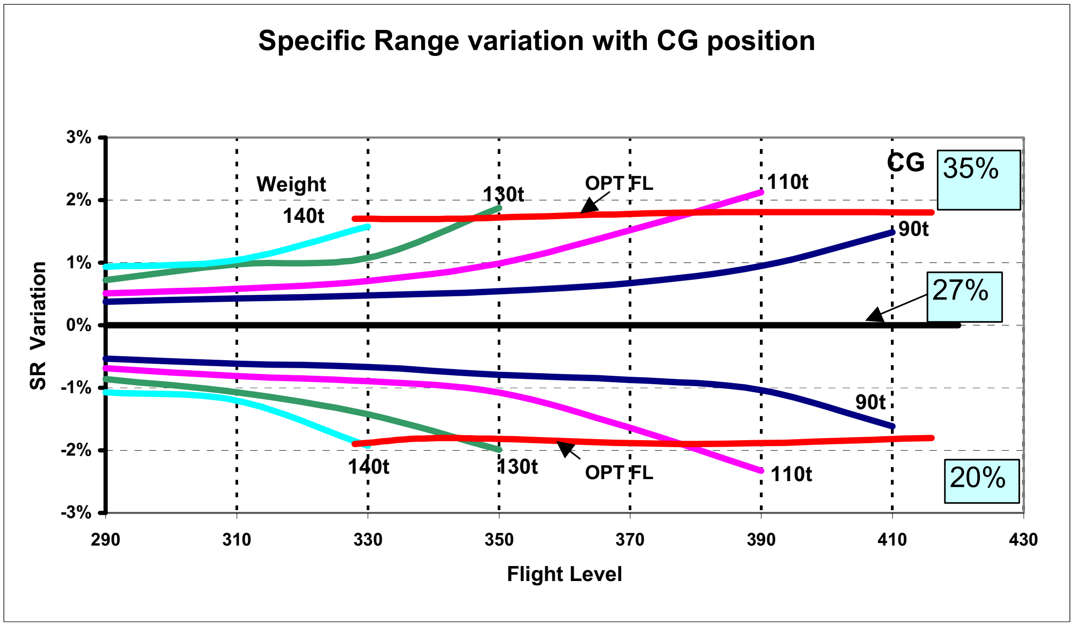
AIRBUS has created a trim tank transfer system that controls the center of gravity of the airplane. This system is installed on some A300 and A310 aircraft and all A330 and A340 aircraft. When an airplane with a trim tank is in cruise, the system optimizes the center of gravity position to save fuel by reducing the drag on the airplane. The system transfers fuel to the trim tank (aft transfer) or from the trim tank (forward transfer). This movement of fuel changes the center of gravity position. The crew can also manually select forward fuel transfer.

The Fuel Control and Management Computer (FCMC) calculates the center of gravity of the airplane from various parameters including input values (Zero Fuel Weight or Gross Take-off Weight and the associated CG) and the fuel tank contents. It continuously calculates the CG in flight. From this calculation, the FCMC decides the quantity of fuel to be moved aft or forward in flight to maintain the CG between the target value and 0.5% forward of the target band.

Usually one initial aft fuel-transfer is carried out late in the climb to bring the CG within this band. During the flight there are several smaller forward movements as the fuel burn moves the CG more aft. Finally a forward transfer is made as the aircraft nears its destination to bring the CG within the landing CG range.

4.1.3 INFLUENCE ON FUEL CONSUMPTION

The following graph shows the change in fuel consumption, expressed in terms of specific range (nm per kg of fuel), for both a Forward (20%) and an Aft (35%) CG position compared to a mid CG position of 27% at cruise Mach.



This graph, which is for the A310-203, shows the advantage of flying at aft CG. Also shown are the optimum altitude lines and these show the effects of CG to be constant at these altitudes, with almost no variation with aircraft weight. Other aircraft have similar shape curves with similar optimum altitude characteristics (except the A320 family). The following table summarizes the effect of CG on specific range at the optimum altitude :

Aircraft Type	Aft CG(35-37%)	Fwd CG(20%)
A300-600	+1.7%	-0.9%
A310	+1.8%	-1.8%
A330	+0.5%	-1.3%
A340	+0.6%	-0.9%

For the A300/A310 reference CG is 27% and aft CG is 35%.

For the A330/A340 reference CG is 28% and aft CG is 37%.

At maximum altitude, the change in fuel consumption given in the table is larger by up to 1%. However no benefit is obtained, as the specific range (SR) is lower at aft CG at maximum altitude than at mid CG at optimum altitude.

For aircraft that are not fitted with automatic center of gravity management, not all these advantages may be realized because of the normal forward and rearward shift of CG in flight due to fuel burn. In addition loading these aircraft at max fuel to an aft CG could prove difficult.

The **A320 family** does not show the same SR variation with CG as the other aircraft. The aft CG produces worst SR at FL290, crossing over to show an improvement at higher flight levels. The SAR variation is much smaller also. This is due to a complex interaction of several aerodynamic effects. The SAR can be considered effectively constant with CG position. Loading is therefore not critical for fuel economy for the A320 family.

In order to assess the overall impact of CG variation on fuel burn, it must be assessed on a complete sector. The following table shows increases in fuel consumed with a more forward CG. It is expressed as kg per 1000nm sector per 10% more forward CG for the max variation case (high weight, high flight level) with no in flight CG shift. The fuel increment in kg is also given for the Forward (20%) position, compared with the Aft (35 or 37%) position, for a typical sector.

Fuel Burn Increase with a more Forward CG

Aircraft types	Fuel increment KG/1000nm/10%CG	Typical Sector distance (nm)	Fuel increment per sector (kg)
A300-600	240	2000nm	710
A310	110	2000nm	330
A319/A320/A321	Negligible	1000nm	Negligible
A330-200	70	4000nm	480
A330-300	90	4000nm	600
A340-200	90	6000nm	900
A340-300	80	6000nm	800
A340-500	150	6000nm	1550
A340-600	130	6000nm	1300

4.2 TAKEOFF WEIGHT

4.2.1 INTRODUCTION

Another way to save fuel is to avoid excess take-off weight, which consists of the operating empty weight of the aircraft plus the payload plus the fuel.

In addition accurate knowledge of weight is an important factor needed to ensure that fuel burn predictions are met. This gives pilots confidence in the flight plans thus reducing the tendency to carry excess fuel.

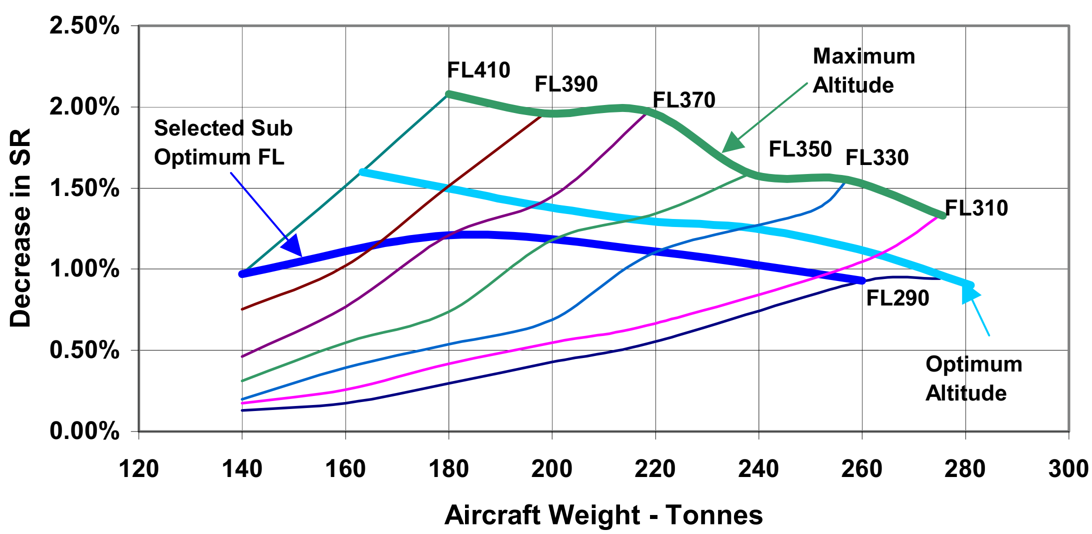
4.2.2 OVERLOAD EFFECT

The specific range, flying at given altitude, temperature and speed depends on weight. The heavier the aircraft, the higher the fuel consumption.

In addition, fuel savings can be made during climb since the aircraft would reach its optimal flight level earlier if it were lighter.

The effect of overloading with respect to the in-flight weight is shown on the following graph, for an excess load of 1% of MTOW (2600kg) in cruise for an A340-313 This shows the increase in specific range penalty with both weight and altitude. Maximum and optimum altitudes are shown together with selected sub optimum flight levels representing the choice of a FL below the Optimum instead of above it. For example, at 220t the optimum altitude is just under FL 350. If we select FL 330 1% extra MTOW will decrease the specific range by just under 1.2%

Specific Range Penalty for Excess Weight of 1% MTOW
A340-313 ISA MN 0.82



The characteristic curves for the other aircraft types have a similar shape. Calculating the weight effect on specific range on all Airbus aircraft in accordance with the lower boundary of typical flight levels gives an average reduction of 1% of SR for a weight increase of 1% of Maximum Take-off Weight. The scatter in this value is generally within .2%.

At the higher altitudes, obtainable at lower weights, the previous picture shows that the SR reduction can increase to 1.5%

Overloading affects not only the trip fuel but also the reserves and requires increased fuel uplift for a specific mission. The following table shows the effect of 1 tonne/1000nm and also 1% of basic MTOW for a typical sector, both at optimum altitude, assuming maximum passengers and some freight.

Aircraft types	Payload	Weight Increase	Stage	Fuel Penalty 1000nm/t	Fuel penalty per sector	Extra Reserves
A300-600	31000 kg	1705 kg	2000 Nm	93 kg	320 kg	100 kg
A310-300	26560 kg	1500 kg	2000 Nm	59 kg	240 kg	90 kg
A318	14650 kg	640 kg	1000 Nm	31 kg	30 kg	30 kg
A319	13000 kg	590 kg	1000 Nm	38 kg	50 kg	40 kg
A320	17200 kg	735 kg	1000 Nm	43 kg	60 kg	45 kg
A321	19100 kg	890 kg	1000 Nm	48 kg	55 kg	50 kg
A330-200	29800 kg	2300 kg	4000 Nm	49 kg	460 kg	100 kg
A330-300	29800 kg	2300 kg	4000 Nm	47 kg	440 kg	100 kg
A340-200	29000 kg	2535 kg	6000 Nm	74 kg	1130 kg	170 kg
A340-300	29000 kg	2535 kg	6000 Nm	87 kg	1330 kg	230 kg
A340-500	35700 kg	3680 kg	6000 Nm	64 kg	1410 kg	210 kg
A340-600	42250 kg	3650 kg	6000 Nm	65 kg	1420 kg	210 kg

Although the A320 family show considerably lower fuel burn penalties than the other aircraft, the total fuel penalty is of a similar order due to the high number of sectors per day. It can readily be seen that a 1% weight penalty has a significant impact on fuel costs when looked at on a yearly basis for a fleet of aircraft.

4.2.3 AIRCRAFT OPERATING WEIGHT

The operating empty weight of an aircraft is defined as the manufacturer's weight empty plus the operator's items. The latter include the flight and cabin crew and their baggage, unusable fuel, engine oil, emergency equipment, toilet chemicals and fluids, galley structure, catering equipment, seats, documents, etc.

The OEW of new aircraft, even in the same fleet, can vary significantly, due to specification changes, build differences and normal scatter. Also aircraft generally get heavier all through their operational life. This is due to repair schemes, service bulletins, equipment upgrades, dirt, rubbish and moisture accumulation and unnecessary equipment and supplies.

This variation in weight requires regular monitoring for flight planning purposes. In general most weight growth is inevitable and it cannot be controlled at the operational level. However the airline has to be sensitive to these problems and efforts have to be made in order to avoid excess weight, such as dirt, rubbish and unnecessary equipment and supplies. It should be noted that 100kg of excess weight requires an additional 5000kg of fuel per year per aircraft.

4.2.4 PAYLOAD

The most important part of the take-off weight from an airlines point of view is the payload (passengers and freight). Generally the weight of passengers, carry-on baggage and checked bags are defined in the operating rules by the authorities such as the JAA or the FAA. Most operators use standard weights although other values may be used if they can be statistically demonstrated through surveys. In general there is not much an operator can do to change the situation. However they should be aware of the rules and their validity. If the weights do not seem appropriate then an operator should consider conducting a survey.

As each freight consignment is weighed, the only influence it can have on fuel economy is its location and hence the aircraft CG.

4.2.5 EMBARKED FUEL

Fuel is loaded onto the aircraft to be used as follows:

1. Start-up Fuel
2. Taxi Fuel
3. Trip Fuel
4. Reserve Fuel
5. Fuel for Transportation
6. APU Fuel

In order to avoid unnecessary fuel weight, the flight must be planned very precisely to calculate the exact fuel quantity to be embarked. Flight planning should be based on aircraft performance monitoring by taking into account performance factors derived from specific range variations. In addition the planning should be based on the appropriate optimized techniques using the best achievable routing and flight levels.

More detailed information on this subject is given later in this brochure.

4.3 FLIGHT PLANNING

The fundamental requirement for achieving fuel economy and reduction of operating costs is a quality Flight Planning System.

A good flight planning system will produce an **optimized route**, in terms of track, speeds and altitudes, which meets the operator's economic criteria. This track and vertical profile must be normally achievable in operation, given the constraints of ATC, climb rates, descent rates, etc.

Climb, cruise and descent **techniques** and cruise **flight levels** should be optimized in accordance with the operator's criteria, for both the sector and the diversion. This is covered in much more detail in this brochure.

It will be based on **good quality data** (temperature, wind, aircraft weight, payload, fuel uplift, etc)

It will be use the **correct aircraft performance** and will include an individual aircraft performance factors derived from an ongoing aircraft performance monitoring (APM) program (see "Getting to Grips with Aircraft Performance Monitoring").

Having established the climb, cruise and descent techniques, it should be verified from time to time that the aircrews are using these techniques

The fuel **reserves** will be based on a policy that aims at obtaining the minimum values required within the regulations.

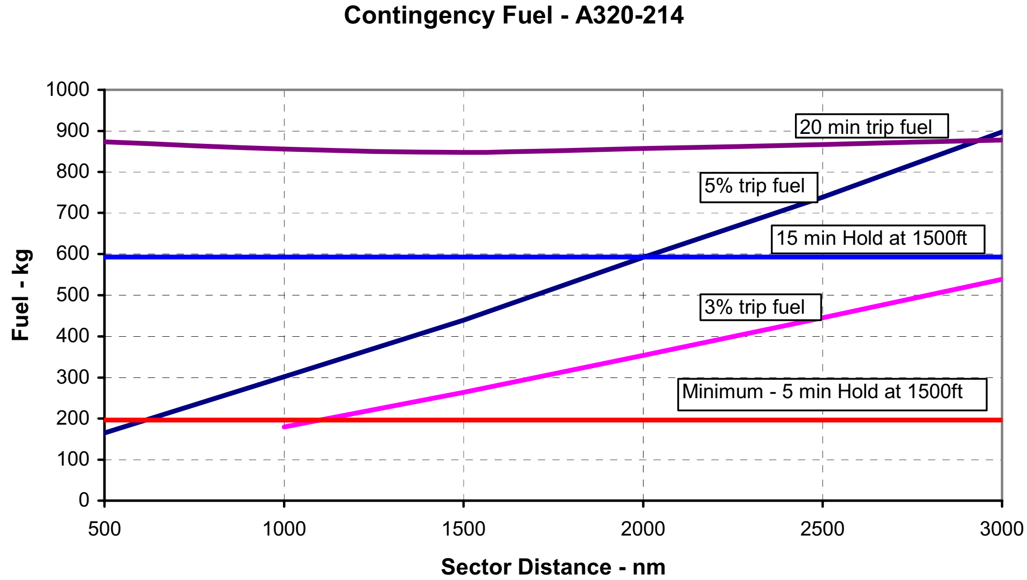
Within JAR OPS, there are several definitions of **Contingency** fuel, depending on diversion airfields, fuel consumption monitoring, etc. Full details can be found in "Getting to Grips with Aircraft Performance", but briefly the fuel is the greater of two quantities:

1. <u>5 minutes hold</u> fuel at 1500 feet above destination at ISA

2. One of the following quantities:
   <u>5% of trip</u> fuel,
   <u>3% of trip fuel</u> with an available en route alternate airport
   <u>15 minutes hold</u> fuel at 1500 feet above the destination at ISA
   <u>20 minutes trip</u> fuel**,** based upon trip fuel consumption.

The last 3 options require airworthiness approval and the last 2 options require fuel consumption monitoring with fuel based on results. What we can conclude is that depending on the flight distance, there is a lowest contingency fuel.

The following graphs show the different contingency fuel quantities for different distances for an A320.



The graphs for other members of the A320 family are similar and indicate that below about 500nm, the contingency fuel is set by the minimum 5-minute hold value. Above about 1000nm, contingency fuel can be reduced to 3% of trip fuel if there is an en-route alternate available. If not, reductions can be made above about 2000nm by using the 15-minute destination hold option, which always requires less fuel than the 20 minute trip fuel option.

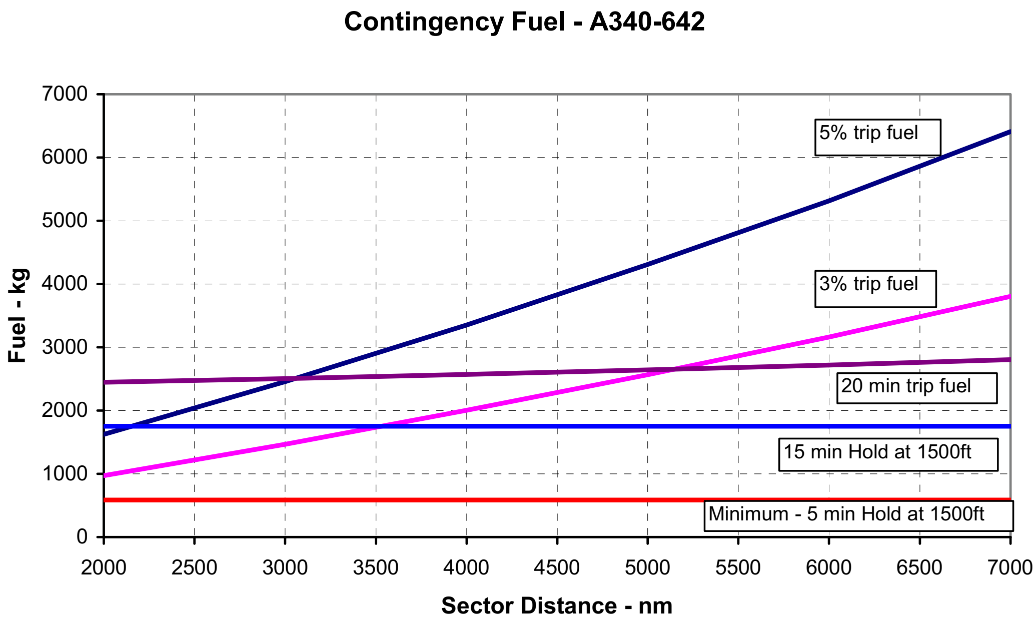
The graphs for the other aircraft show different characteristics because of their longer-range capability.

The A340-600 picture, on the following page, indicates that with no en-route alternate the 15-minute destination hold requirement enables the contingency fuel to be reduced above 2150nm. An en-route alternate will give more benefit until 3500nm, beyond which the 15-minute destination hold minimises the contingency fuel requirement. The A340-500 is similar.

The A300, A310, A330 and other A340's have slightly different critical distances as follows:

5% trip fuel/15-minute hold	1700 to 1900nm.
3% trip fuel/15-minute hold	2800 to 3200nm

However these will also vary with weight, winds, temperature, etc so the limiting reserve should always be checked. Each aircraft type will show critical sector distances beyond which a change in contingency policy will yield benefits.



One further method of reducing the contingency fuel is by using a Decision Point or **Redispatch** Procedure. This involves the selection of a decision point where the aircraft can either continue to the destination as the remaining fuel is sufficient, or it can reach a suitable proximate diversion airport. More details are given in "Getting to Grips with Aircraft Performance".

To minimize the **alternate** fuel, the alternate airports should be chosen as near as possible to the destination.

Both the JAA and FAA do not require the alternate fuel reserve in certain cases, depending on meteorological conditions and the suitability of the airport. More details are given in "Getting to Grips with Aircraft Performance".

Another part of the reserves is the **extra fuel**, which is at the Captain's discretion.

There are many reasons why this extra fuel is necessary. It could be due to uncertain weather conditions or availability of alternate and destination airfields, leading to a probability of re-routing. However it is often due to lack of confidence in the flight planning and the natural desire to increase reserves.

This is the one area where a significant impact can be made through accurate flight planning. With this in place, the aircrew will see that the flight plans fuel burns are being achieved in practice. They will realize that the planned reserves are adequate and that there is no need for more.

4.4 TAXIING

Good estimate of taxi times are required. Actual times need to be monitored and standard estimates changed as necessary. Jet engine performance is optimised for flight conditions, but all aircraft spend considerable time on the ground taxiing from the terminal out to the runway and back. This time has increased due to airport congestion, and increased airport size. This all leads to a waste of precious time and fuel.

Only using one engine for taxiing twin-engine aircraft, or two engines for four-engine aircraft can give benefits in fuel burn. Such procedures need to be considered carefully, and operators have to define their field of application.

Airbus provides standard procedures in the Flight Crew Operating Manual (FCOM) for such operations. The following factors regarding one or two engine out taxi should be considered carefully prior to its incorporation in the operators standard operating procedures:

1. This procedure is not recommended for high gross weights
2. This procedure is not recommended for uphill slopes or slippery runways
3. No fire protection from ground staff is available when starting engine (s) away from the ramp
4. Reduced redundancy increases the risk of loss of braking capability and nose wheel steering.
5. FCOM procedures require not less than a defined time (from 2 to 5 minutes depending on the engine) to start the other engine(s) before take off. On engines with a high bypass ratio, warm-up time prior to applying maximum take off thrust has a significant effect on engine life.
6. Mechanical problems can occur during start up of the other engine(s), requiring a gate return for maintenance and delaying departure time.
7. FCOM procedures require APU start before shutting down the engine after landing, to avoid an electrical transient.
8. FCOM procedures require not less than a defined time before shutting down the other engine(s) after landing. On engines with a high bypass ratio, the cool-down time after reverse operation, prior to shut down has a significant effect on engine life.
9. If an operator decides to use one or two engine out taxi, then FCOM recommendations about which engine(s) to use should be followed.

As engine-out taxi requires more thrust per engine to taxi and maneuver, caution must be exercised to avoid excessive jet blast and FOD. More thrust is necessary for breakaways and 180 degrees turns.

On twin-engine aircraft slow and/or tight taxi turns in the direction of the operating engine may not be possible at high gross weight.

Single engine taxi may also be considered at low weights to avoid excessive use of the brakes to control the acceleration tendency with all engines. This brake use would be detrimental to carbon brake life.

The following table gives an indication of the advantages of engine out taxi for 8 of the 12 minutes total taxi time, leaving 4 minutes warm up time.

Fuel savings with Engine out taxi

Aircraft types	12 minutes taxi (all engines)	12 minutes taxi (8 with engine out)	Engine Out taxi savings
A300-600	300kg	200kg	100kg
A310	240kg	160kg	80kg
A318	120kg	80kg	40kg
A319	120kg	80kg	40kg
A320	138kg	92kg	46kg
A321	162kg	108kg	54kg
A330	300kg	200kg	100kg
A340-200/300	300kg	200kg	100kg
A340-500/600	420kg	280kg	140kg

For engine out or all engines taxi, the use of a slow taxi speed costs fuel and time. A burst of power should be used to get the aircraft to taxi speed, then the power should be reduced to idle. However 30kt should not be exceeded.

4.5 FUEL FOR TRANSPORTATION

The normal message regarding fuel burn is that it is more economical to carry the minimum amount required for the sector. However there are occasions when it is economic to carry more fuel. This is when the price of fuel at the destination airfield is significantly higher than the price at the departure airfield.

However, since the extra fuel on board leads to an increase in fuel consumption the breakeven point must be carefully determined.

K is the **transport coefficient**:

$$\boxed{K = \frac{\Delta TOW}{\Delta LW}}$$

The addition of one tonne to the landing weight, means an addition of K tonnes to the take-off weight.

For example, if K=1.3 and 1300 kg fuel is added at the departure, 1000 kg of this fuel amount will remain at the destination. So carrying one tonne of fuel costs 300 kg fuel more.

<u>The extra-cost of the loaded fuel at departure is</u>

Fuel weight x departure fuel price $(\Delta TOW \times P_d = \Delta LW \times K \times P_d)$

<u>The cost saving of the transported fuel is</u>

Transported fuel x arrival price $(\Delta LW \times P_a)$

<u>The cost due to a possible increase in flight time is</u>

Flight time increase x cost per hour $(\Delta T \times C_h)$

It is profitable to carry extra fuel if the cost saving exceeds the extra fuel loaded cost plus the extra time cost.

$$(\Delta LW \times P_a) > (\Delta LW \times K \times P_d) + (\Delta T \times C_h)$$

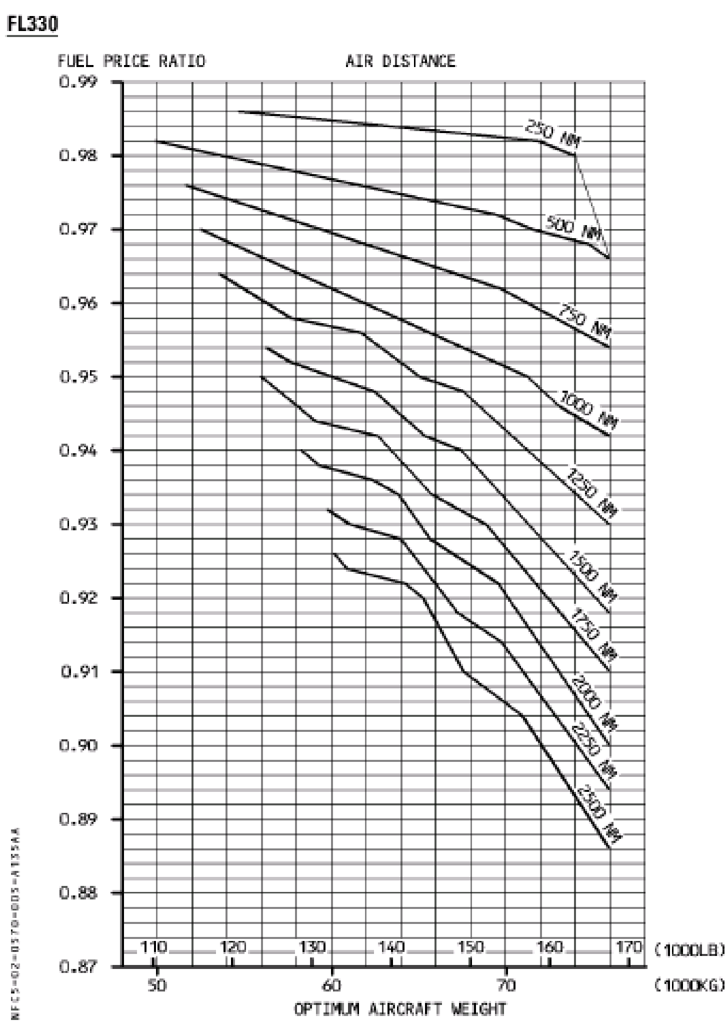
That is to say:

$$\Delta LW\ (P_a - K \times P_d) - (\Delta T \times C_h) > 0$$

Therefore, if $\Delta T=0$, it is profitable to carry extra fuel if the arrival fuel price to departure fuel price ratio is higher than the transport coefficient K.

$$\frac{P_a}{P_d} > K$$

Thus carrying extra fuel may be of value when a fuel price differential exists between two airports. Graphs in the FCOM assist in determining the optimum fuel quantity to be carried as a function of initial take-off weight (without additional fuel), stage length, cruise flight level and fuel price ratio. The following graph is an example for an A320.



However the needs for accurate fuel planning is necessary to avoid arriving at the destination airport overweight. This could result in the economic benefit being eroded or negated due to extra hold time or circuits.

4.6 AUXILIARY POWER UNIT

The Auxiliary Power Unit (A.P.U.) is a self-contained unit which makes the aircraft independent of external pneumatic and electrical power supply and environmental conditioning.

A.P.U. fuel consumption obviously represents very little in comparison with the amount of fuel for the whole aircraft mission. Nevertheless, operators have to be aware that adopting specific procedures on ramp operations can help save fuel and money.

On the ground, A.P.U. fuel consumption depends on the A.P.U. type load and the ambient conditions. The minimum is when the APU is in the RTL(ready to load) condition. As additional loads, such as Electrical Loads(EL) and Environmental Conditioning System (ECS), are connected, the fuel consumption increases as shown in the following table (ISA, SL conditions).

Aircraft Type	APU Model	RTL	RTL Max EL	Min ECS Max EL	Max ECS Max EL
A320 family	36-300	70 kg/hr	85 kg/hr	105 kg/hr	125 kg/hr
A320 Family	131-9A	75 kg/hr	95 kg/hr	115 kg/hr	125 kg/hr
A330, A340	331-350	120 kg/hr	140 kg/hr	175 kg/hr	210 kg/hr
A340-500/600	331-600	160 kg/hr	180 kg/hr	225 kg/hr	290 kg/hr

A.P.U. specific procedures to save fuel have to be defined by the operators. One extra minute of A.P.U. operation per flight at 180 kg/hr fuel flow, means an additional 3000 kg per year per aircraft. This will also result in increased maintenance costs.

They have to choose between using ground equipment (Ground Power Unit, Ground Climatisation Unit, Air Start Unit) and the A.P.U. This choice depends on several parameters and each operator needs to determine the benefits at each airport and at each turnaround.

Such parameters can include length of turnaround, ambient conditions, cost of ground connections, time delay to get connected, suitability and quality of ground equipment, passenger load, local noise restrictions, etc.

For a **long turnaround** or **night stop** the G.P.U. is the best choice as time considerations are not prevailing. It saves both fuel and A.P.U. life. So operators are advised to use ground equipment if of a good quality, and to try to conclude agreements with airport suppliers to get preferential prices.

However, for a **short turnaround** (45 minutes on average), the use of A.P.U. may be preferable to limit A.P.U. start cycles and improve reliability, even if it is not fully used during the turnaround. It is better to operate with A.P.U. at RTL than to shut it down and perform a new start cycle soon after shut down. Lack of suitable ground power may also require the use of APU. The use of APU may also be preferable to avoid excessive hook up charges or to reduce turnaround time.

Some airport regulations restrict the use of the APU to a defined time prior to departure time and after the arrival.

For **extremely short turnarounds**, complete engine shut down would have a cyclic cost impact, and therefore the turnaround could be made without APU. However a main engine can sometimes not meet the ECS demand in high load conditions (hot days).

The disconnection of ground equipment supplies and the start of A.P.U. must be coordinated with A.T.C. pushback/slot requirements. A **one-minute anticipation** in each A.P.U. start will lead to a significant amount of fuel saving during a year (2000 to 4000 kg depending on A.P.U. types).

Engine start up should also, if possible, be carefully planned in conjunction with A.T.C. If pushback is delayed, it is preferable to wait and use A.P.U. for air conditioning and electrical requirements. Engine start time is critical, and the engines should not be started until ready to go.

The following table assuming typical engine fuel flows, shows extra fuel consumption by using one engine instead of the A.P.U. for 1 minute, assuming maximum electrical load and minimum ECS:

Extra fuel when using Engine instead of APU

Aircraft Type	A.P.U. type	Engine FF kg/hr/eng	APU FF kg/hr	Extra Fuel for 1 minute
A300 GE	331-250	520	150kg	6kg
A310 GE	331-250	520	150kg	6kg
A320 family CFM	36-300	300	105kg	3kg
A330 GE	331-350	520	175kg	6kg
A330 RR	331-350	720	175kg	9kg
A340 CFM	331-350	300	175kg	2kg
A340 RR	331-600	480	275kg	4kg

In overall economic terms, the benefits of APU operation are not just confined to fuel usage. The hourly maintenance costs of an APU are cheaper than the aircraft powerplant, so reducing ground running time on the engines can significantly reduce the operating costs.

4.7 AERODYNAMIC DETERIORATION

Some of the most severe penalties in terms of fuel consumption are caused by increased drag resulting from poor airframe condition. Normal aerodynamic deterioration of an aircraft over a period of time can include the incomplete retraction of moving surfaces, damaged seals on control surfaces, skin roughness and deformation due to bird strikes or damage caused by ground vehicles, chipped paint, mismatched doors and excessive gaps. Each deterioration incurs a drag increase, and this increased drag is accompanied by increased fuel consumption.

This subject is covered fully in the brochure "Getting Hands-On Experience with Aerodynamic Deterioration".

The following table gives the highest deterioration effect in each category for the three aircraft families as increased sector fuel consumption in Kg, based on typical utilization figures.

Category	Condition	A300/310	A320 Family	A330/340
Misrigging	Slat 15mm	90	60	270
Absence of Seals	Flap (chordwise)	30	14	90
Missing Part (CDL)	Access Door	50	13	150
Mismatched Surface	Fwd Cargo Door 10mm step for 1m	20	11	80
Door seal leakage	Fwd Pax Door 5cm	2	1	5
Skin Roughness	1 m^2	21	13	105
Skin Dents	Single	2	1	2
Butt joint gaps	Unfilled	0.2	0.1	0.6
Butt Joint Gaps	Overfilled	3	2	7
External Patches	1 m^2 3mm high	6	3	16
Paint Peeling	1 m^2 leading edge slat	12	8	57
	Sector Distance	2000nm	1000nm	4000/6000nm

5. IN FLIGHT PROCEDURES

When an aircraft arrives at the end of the runway for take-off, it is the flying techniques (speed, altitude, configuration, etc) that have the biggest influence on fuel economy. Disciplined flight crews adhering to a flight plan based on the operator's priorities can save much fuel and/or costs.

This part intends to give recommendations to flight crews on the means to save fuel during the flight. It reviews the different phases of the flight, that is to say:

- Take-off and Initial Climb
- Climb
- Cruise
- Descent
- Holding
- Approach

5.1 TAKE-OFF AND INITIAL CLIMB

5.1.1 INTRODUCTION

There are many variations in take-off technique that can directly affect the fuel burn. In general the effects are very dependent on the airframe/engine combination as well as aircraft weight, airfield altitude and temperature. The following fuel effects are representative values.

5.1.2 BLEEDS

For take-off, full bleeds can be used or one can consider selecting packs off or APU bleed on to improve take-off performance. Selecting packs off **without APU** will also improve fuel burn. The normal procedure would then be to select pack 1 on after climb thrust is selected and pack 2 on after flap retraction. This has the effect of reducing fuel burn by 2-3 kg on an A320 increasing to 5-10 kg on an A340-500/600.

With APU bleed the engine fuel burn will be decreased by the same amount. However with APU used from pushback with 12minutes taxi, the additional APU fuel burn is 30kg for an A320 and 60-70kg for an A340.

In economic terms, the APU fuel and maintenance cost is largely offset due to decreased engine maintenance costs bleeds off (higher flex temp).

5.1.3 CONFIGURATION

This effect is very dependent on the variables mentioned in the introduction, plus the choice of VR and V2. However the trend is always the same , with high flap/slat configurations (more extended) using more fuel than the lowest setting. Typical penalties/takeoff of higher flap settings compared with the low flap settings Conf 1+F are shown below (note that for the A300/A310 Conf 1+F, Conf 2 and Conf 3 corresponds to the Flap 0,15 and 20 configuration respectively).

Aircraft	Conf 2	Conf 3
A300/A310	1- 5kg	15kg
A320	3-5kg	8-13kg
A330	12kg	24kg
A340	30kg	50kg

These figures assume Full take-off thrust. The advantage of Conf 1+F increase with reduced power take-offs.

5.1.4 SPEEDS

During a non limiting full power take-off, the use of the higher speeds appropriate to flex thrust instead of optimized speeds appropriate to the actual temperature can reduce the fuel burn by up to 8kg.

5.1.5 FLEX THRUST

Compared to a full thrust take-off, flex thrust will generally increase fuel burn. The increased time at low level offsets the slight reduction in fuel flow induced by the lower thrust. Typical increases are as follows:

Aircraft	Conf 1+F	Conf 2	Conf 3
A300/A310	10kg	10kg	10kg
A320	1kg	5kg	5kg
A330	0	0	0
A340	5kg	20kg	25kg

5.1.6 NOISE FLIGHT PATHS

The effect of an ICAO type A noise flight path, with climb thrust selected at 800ft and clean up delayed until 3000ft is generally to increase fuel burn compared to the standard take-off with power reduced at 1500ft. The actual distance to a fixed height, say 5000ft, varies very little with configuration. The main effect is the different altitude – speed history experienced by the engines. Typical values are as follows:

Aircraft	Conf 1+F	Conf 2	Conf 3
A320	-4kg	+5kg	+2kg
A330	+100kg	+100kg	+115kg
A340	+90kg	+130kg	+125kg

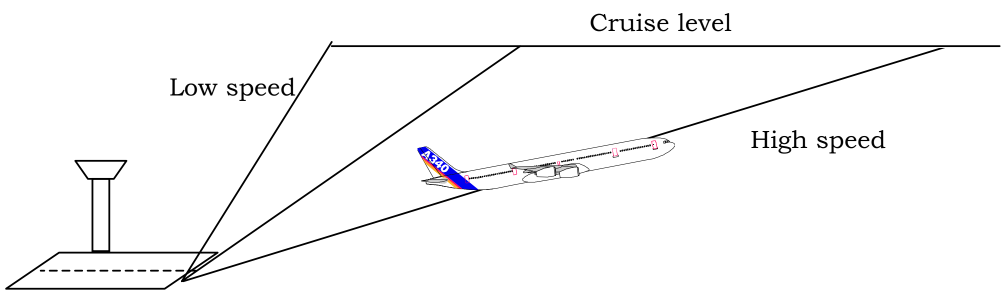
5.1.7 COURSE REVERSAL

In the event that a course reversal is required after take-off, then much distance can be saved using a lower initial climb speed. Suppose ATC require an aircraft to maintain runway heading to 6000ft. A lower climb speed will achieve this altitude earlier and thus reduce the ground distance and fuel burnt.

5.2 CLIMB

5.2.1 INTRODUCTION

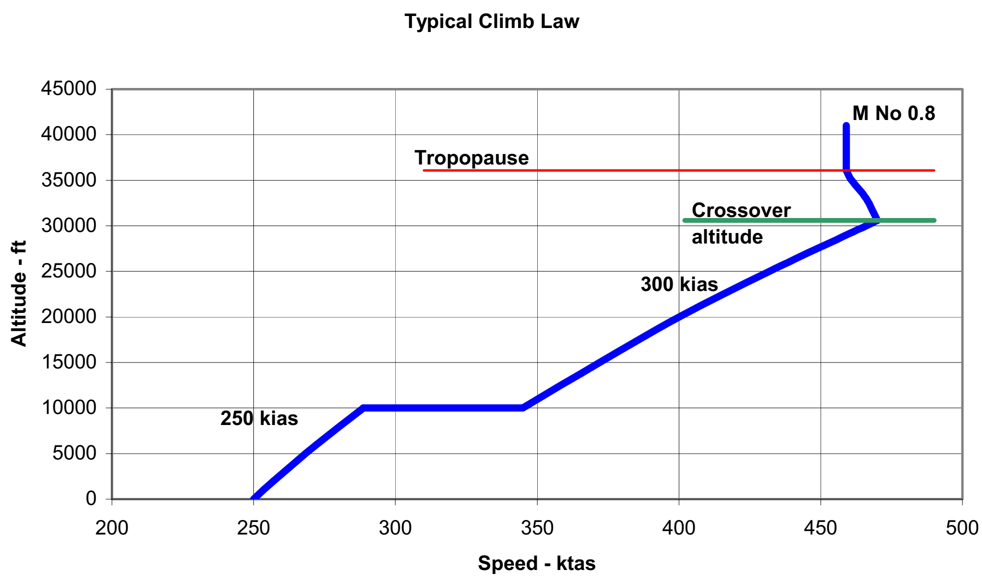
Depending on speed laws, the climb profiles change. The higher the speed, the lower the climb path, the longer the climb distance.



Climb profiles

Climbs are normally performed in three phases on a constant IAS/Mach climb speed schedule at max climb thrust, as follows:

- 250 KT indicated air speed (IAS) is maintained until flight level 100, then the aircraft accelerates to the chosen indicated air speed (e.g. "300kts);
- constant indicated air speed is maintained until the crossover altitude;
- constant Mach number is maintained until top of climb;



The crossover altitude is the altitude where we switch from constant IAS climb to the constant Mach number climb. It only depends on the chosen IAS and Mach number, and does not depend on ISA variation.

During climb, at constant IAS, the true air speed (TAS) and the Mach number increase. Then, during climb at constant Mach number, the TAS and the IAS decrease until the tropopause.

To correctly evaluate the effects of climb techniques, climb and cruise flight must be viewed in relation to each other. A short climb distance for example extends the cruise distance; a low climb speed requires more acceleration to cruise speed at an unfavourable high altitude. One has therefore to consider sectors that cover acceleration to climb speed, climb, acceleration to cruise speed and a small portion of the cruise to the same distance.

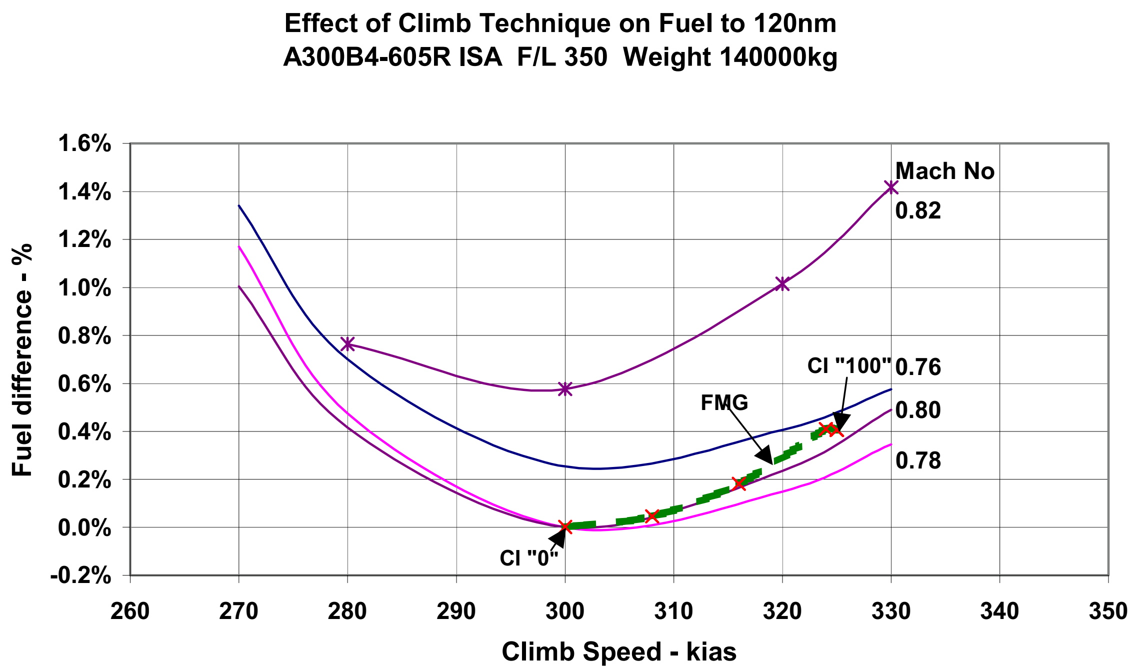
5.2.2 THE EFFECT OF CLIMB TECHNIQUE ON FUEL BURN

This evaluation has been made for all Airbus types, based on a climb to 35000ft, acceleration and cruise to a fixed distance. The assumed cruise speed was 0.78 for the A320 family and 0.8 for the rest.

The reference climb technique is the standard technique given in each FCOM, and is summarized below:

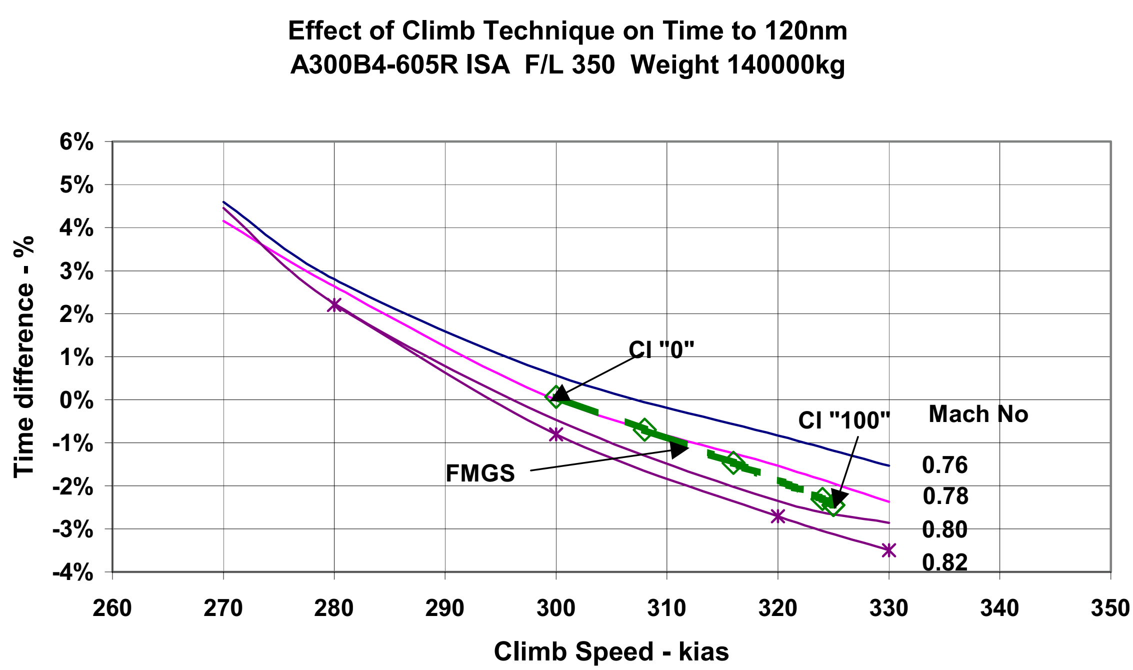
Aircraft types	Speed law
A300-600	250kts/300kts/M0.78
A310 (GE)	250kts/300kts/M0.79
A310 (PW)	250kts/300kts/M0.80
A318/A319/A320/A321	250kts/300kts/M0.78
A330	250kts/300kts/M0.80
A340-200/300	250kts/300kts/M0.78
A340-500/600	250kts/320kts/M0.82

The following chart shows the variation of fuel burn with climb technique over a given climb + cruise distance.



This shows that there is an optimum climb speed and max climb Mach number that produces the lowest fuel burn. This happens to be the standard technique (300kt/0.78). Climbing at 320kt/0.82 will burn 1% more fuel.

However the following chart shows that this is obtained at the **expense of time.**



This time difference plot has the same characteristics for all Airbus aircraft, with the best time being obtained at the highest climb speed and max climb Mach number. Note that although a slow climb speed gets the aircraft to cruise altitude earlier, this requires more acceleration to cruise speed and more cruise to a given distance, making it slower overall.

The fuel difference plot characteristics vary with aircraft type. The A310, A321 and A330 show similar characteristics to the A300 with a best fuel climb speed of about 290 to 300 knots.

The A318, A319 and A320 show better fuel burn at the lower speed range (260 to 280 knots)

The A340 shows better fuel burn at the higher speed range (310-330 knots).

The A310 and A340 are similar to the A300 in showing minimum fuel at a max climb Mach number of 0.78. In fact 0.8 is better for the A340-500/600.

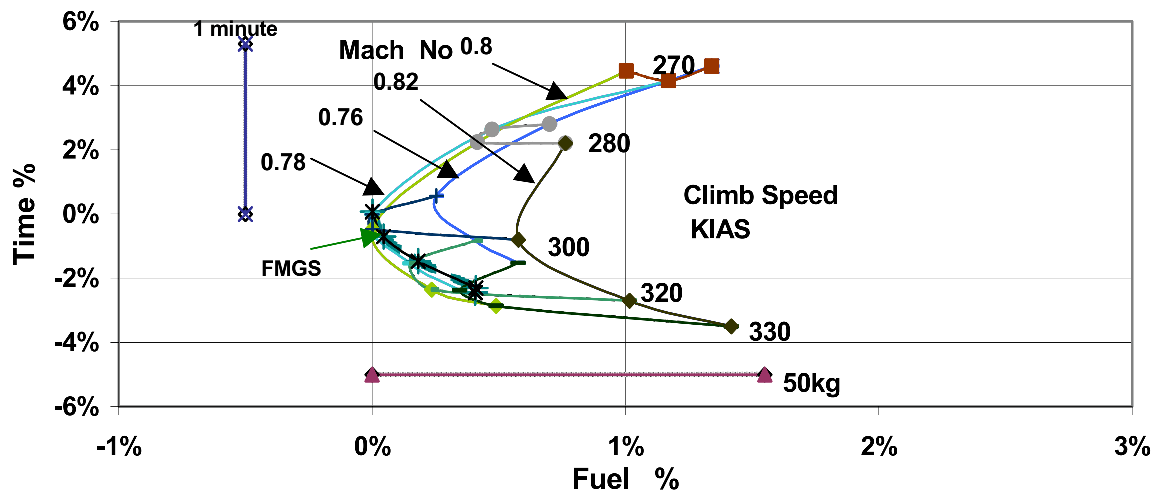
However the A320 family and A330 benefit from the lower Mach No of 0.76.

Thus the A320 family benefits from low climb speeds and the A340 from high climb speeds. This difference arises from the different behavior during climb of twin-engine and four-engine aircraft. Indeed, twin-engine aircraft have a higher thrust than four engine aircraft, as they must satisfy some take-off climb requirements with only one engine operative, compared with 3 engines operative on the quads. This enables them to have a higher rate of climb than four engine aircraft and reach cruise flight levels quicker.

5.2.3 CORRELATION OF FUEL BURN & TIME WITH CLIMB TECHNIQUE

The following chart shows the differences in fuel and time to climb and cruise to a fixed distance with varying climb speed and max climb Mach number relative to the standard technique.

Effect of Climb Technique on fuel and time to 120nm
A300B4-605R ISA F/L 350 Weight 140000kg

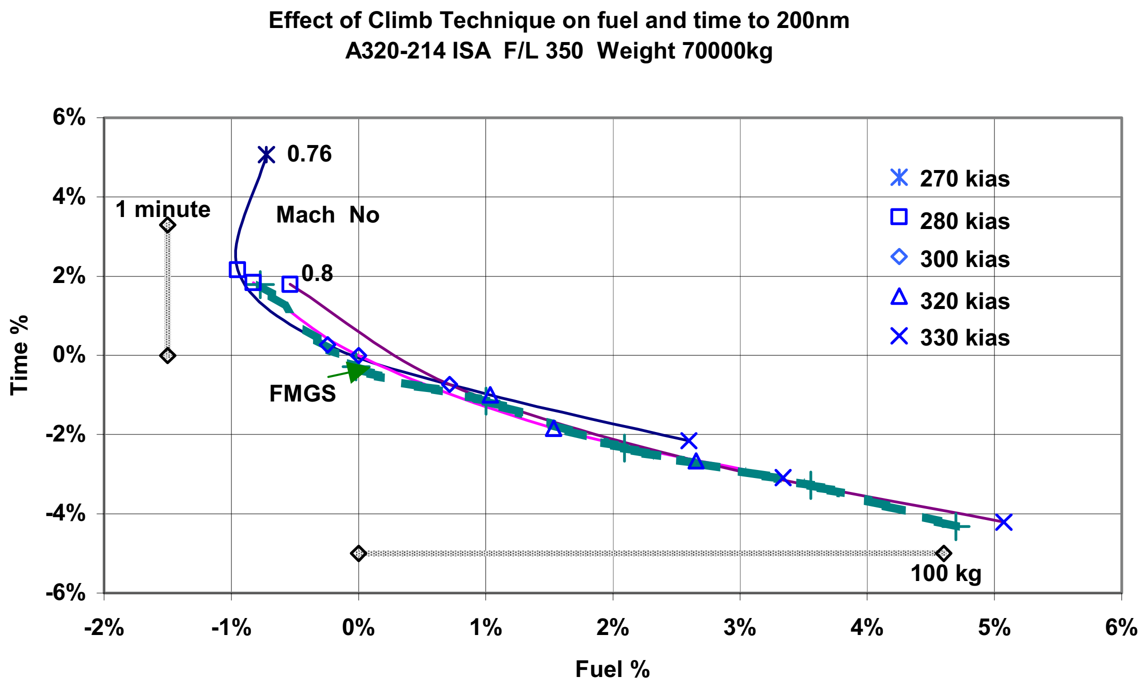


This chart shows that the fastest technique (330/0.82) uses the least time (-3.2%) and the most fuel (+1.5%) whereas the slowest technique (270/0.76) uses the most time (+4.5%) and nearly the most fuel (+1.4%). The least fuel is obtained using a 300/0.78 climb technique. Variation of climb technique can cause a total variation of 1.5% and climb time by 8% for this aircraft.

Also plotted on the charts are lines representing the speeds selected by the FMGS for various cost indices (CI). The left hand point of each line represents a CI of zero (fuel cost priority) and the right hand point represents a CI of 100 (flight time priority). It should be noted how the FMGS line approximates to the lower boundary of the time - fuel difference plot.

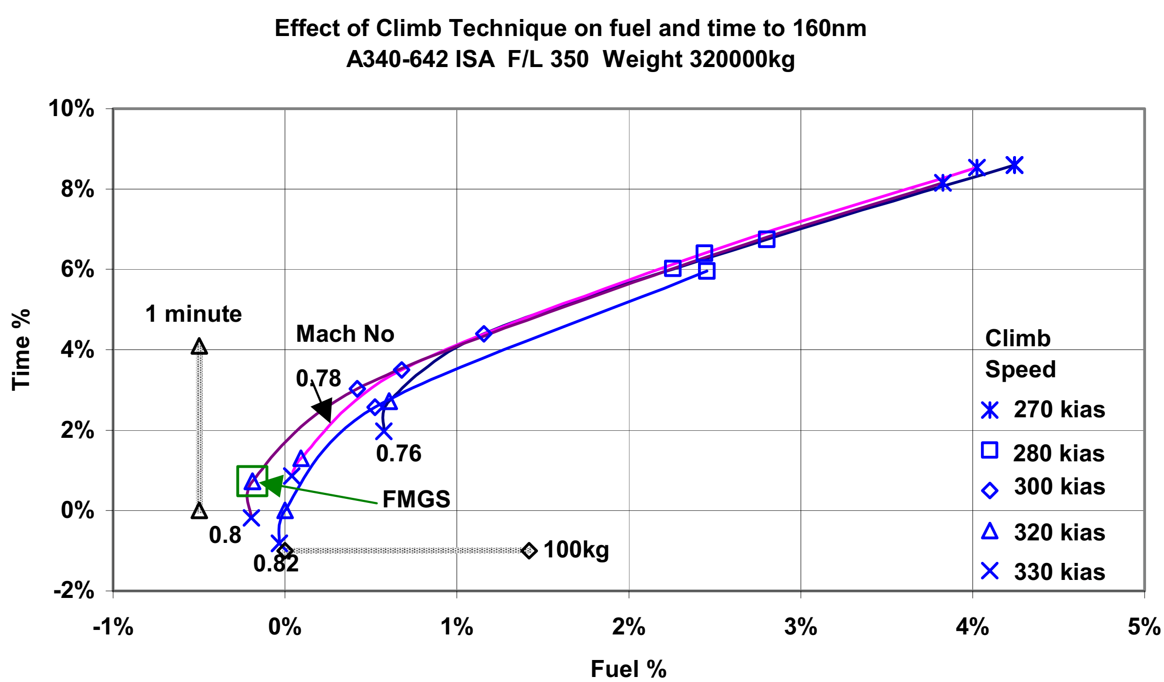
The chart on the following page is for the A320 and shows completely different characteristics.

The different mach numbers all coalesce together and the FMGS line forms the



common boundary. Climb speed increases from the left to the right. Least fuel is obtained using a 0.76/280 technique. Mach No has little influence, but increasing speed from 280 to 330kias decreases time by 6% and increases fuel by 6%.

Completely different characteristics are also shown in the next chart (A340-642).



This shows a common technique is good for both fuel burn and time. The optimum is 320/0.80. There is little Mach No effect, but reducing the speed to 270 kias will increase fuel by 4% and time by 8%. Because the optimum technique is good for both fuel and time, there is a single FMGS point for all cost indeces.

Earlier versions of the A340 showed that some marginal time benefit could be gained by climbing faster. However this would have affected the flight levels achieved. Consequently there is no variation of FMGS climb speed with cost index for all the A340 family.

Appendix A presents some examples of time - fuel charts for other Airbus aircraft.

5.2.4 CLIMB TECHNIQUE COMPARISON TABLES

The following tables show, for various Airbus aircraft, the climb time and fuel variations for a fixed distance, to FL 350, relative to a 300kias reference speed.

Effect of Climb Speed on Fuel

Aircraft	Climb Mach No.	ΔFuel – kg				
		270KT	280 KT	300 KT	320 KT	330 KT
A300	0.78	+40	+15	0	+5	+10
A310	0.79		+5	0	+5	+15
A318/A319/A320	0.78		-15	0	+30	+70
A321	0.78		-10	0	+25	+60
A330	0.80	+15	+5	0	+20	+35
A340–200	0.78	+45	+20	0	+10	+25
A340-300	0.78	+105	+50	0	-5	+20
A340-500/600	0.82		+135	0	-5	-10

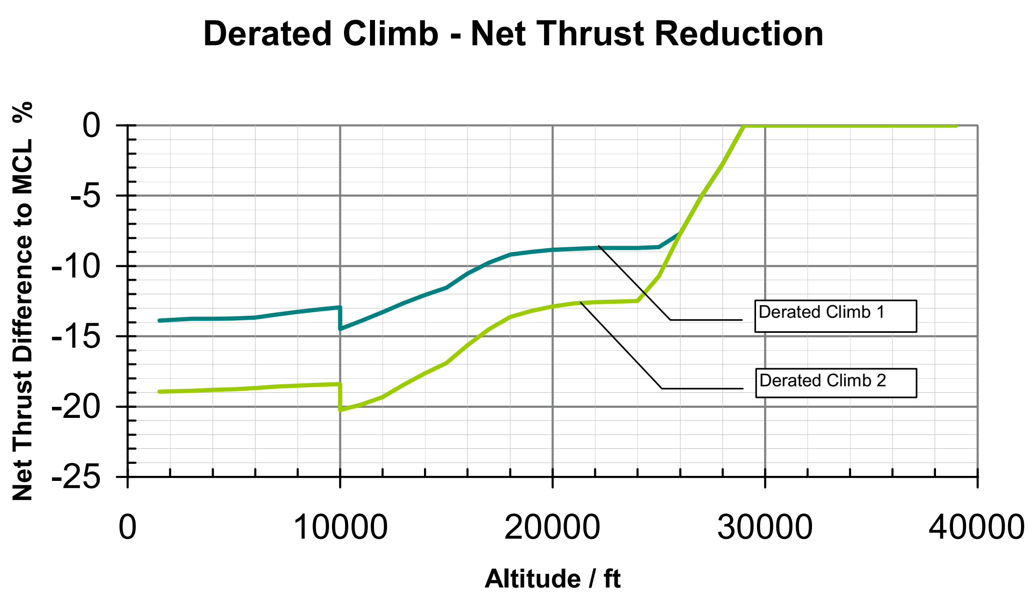
Effect of Climb Speed on Time

Aircraft	Climb Mach No.	ΔTime – minutes				
		270KT	280 KT	300 KT	320 KT	330 KT
A300	0.78	+0.8	+0.5	0	-0.3	-0.4
A310	0.79		+0.5	0	-0.5	-0.6
A318/A319/A320	0.78		+0.5	0	-0.4	-0.8
A321	0.78		+0.8	0	-0.6	-1.0
A330	0.80	+0.9	+0.6	0	-0.4	-0.7
A340–200	0.78	+1.4	+0.8	0	-0.6	-0.8
A340-300	0.78	+1.5	+0.9	0	-0.6	-1.0
A340-500/600	0.82		+0.8	0	-0.6	-0.8

It can be seen from the tables how the optimum techniques are very dependant on the aircraft type, and that a 10kt climb speed change can have a significant impact.

5.2.5 DERATED CLIMB

In order to reduce engine maintenance costs, there are derated climb options available on the A330 and A340 aircraft. There are two levels of derate, D1 and D2. At a certain altitude the derate is washed out such that at Max Climb rating is achieved generally before 30000ft. The following shows a typical derate thrust variation picture, but this will vary with engine and temperature.



However this derate will result in more fuel and time required to reach the same distance. The effect is dependant on aircraft weight, temperature and cruise flight level. The following table gives some typical penalties in ISA conditions to 35000ft.

Aircraft	Weight (kg)	Derate D1		Derate D2	
		Fuel Increase	Time Increase	Fuel Increase	Time Increase
A330-203	190000	5kg	0.5 min	20kg	0.6 min
A330-223	190000	20kg	0.2 min	40kg	0.5 min
A330-343	190000	20kg	0.2 min	40kg	0.5 min
A340-212	240000	65kg	0.9 min	120kg	1.5 min
A340-313	240000	140kg	0.8 min	225kg	1.4 min
A340-313E	240000	140kg	1.0 min	335kg	1.4 min
A340-642	340000	270kg	0.6 min	445kg	1.0 min

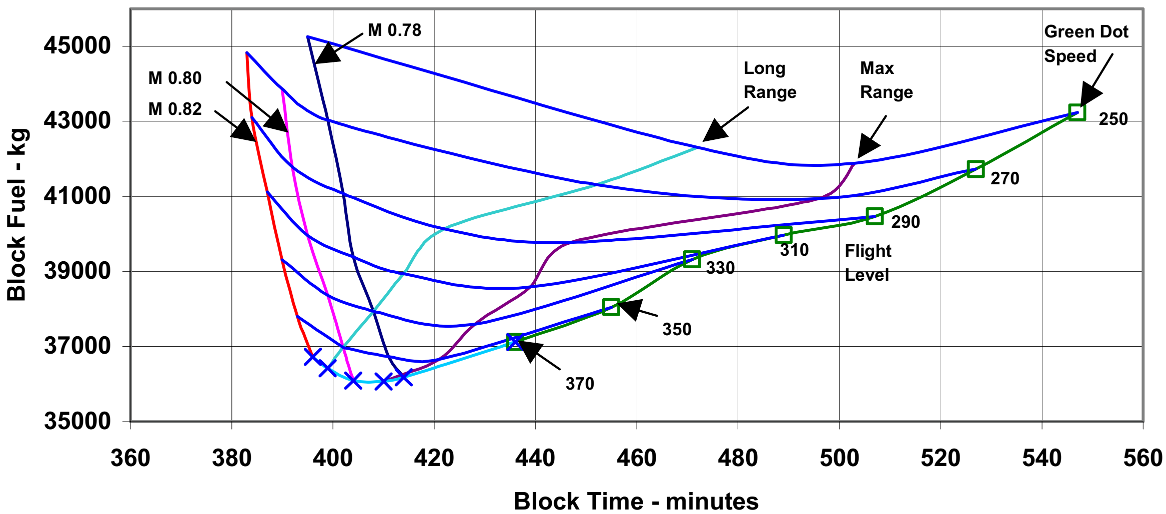
5.3 CRUISE

5.3.1 INTRODUCTION

The cruise phase is the most important phase regarding fuel savings. As it is the longest for long haul aircraft, it is possible to save a lot of fuel. So discipline must be exercised particularly in this phase.

The two variables that most influence cruise fuel consumption are the cruise speed (IAS or Mach Number) and the altitude or flight level. The following shows their influence on a single sector assuming standard climb and descent procedures.

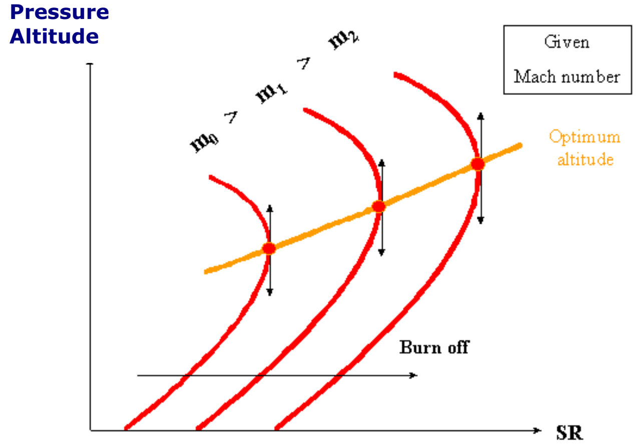
Block Fuel and Time for various Flight Levels and Mach numbers
A330-223 ISA 3000nm Payload 30000kg JAR Reserves



The correct selection of the cruise parameters is therefore fundamental in minimizing fuel or operating cost. This chart shows the normal laws that aircraft consume less fuel when flown slower or when flown higher. However there are limits to these laws. Flying lower than the maximum range speed will increase the block fuel, as will flying higher than an optimum altitude.

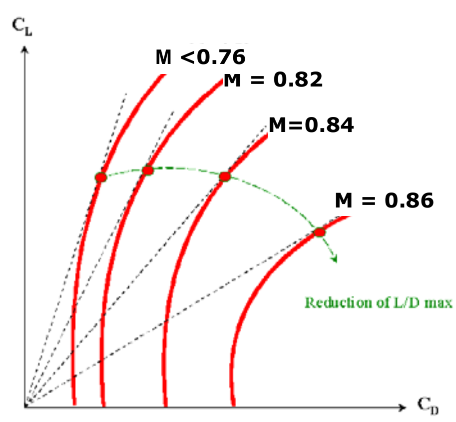
5.3.2 CRUISE ALTITUDE OPTIMISATION

In examining SR changes with the altitude at a constant Mach number, it is apparent that, for each weight, there is an altitude where SR is maximum. This altitude is referred to as "optimum altitude".



Optimum Altitude Determination at Constant Mach Number

When the aircraft flies at the optimum altitude, it is operated at the maximum lift to drag ratio corresponding to the selected Mach number.



High Speed Polar Curve

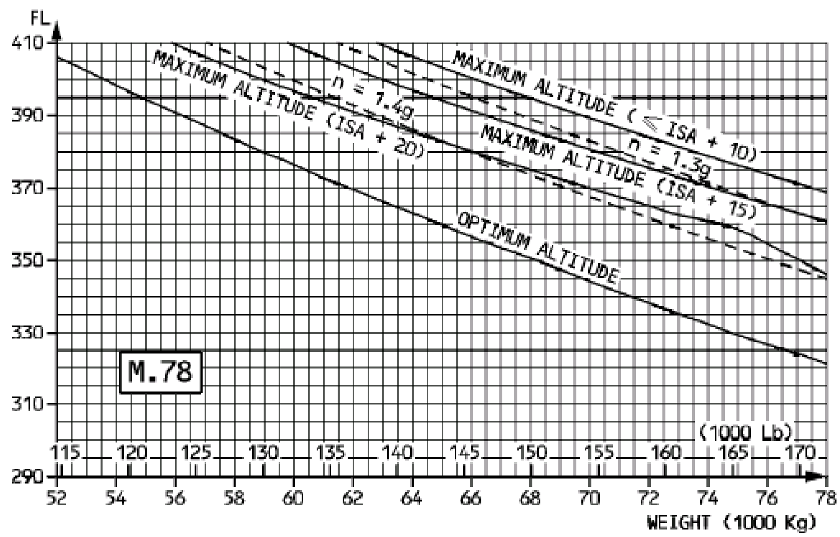
When the aircraft flies at high speed, the polar curve depends on the indicated Mach number, and decreases when Mach increases. So, for each Mach number, there is a different value of $(C_L/C_D)_{max}$, that is lower as the Mach number increases.

When the aircraft is cruising at the optimum altitude for a given Mach, C_L is fixed and corresponds to $(C_L/C_D)_{max}$ of the selected Mach number. As a result, variable elements are weight and outside static pressure (P_s) of the optimum altitude. The formula expressing a cruise at optimum altitude is:

$$\boxed{\frac{\text{Weight}}{P_s} = \text{constant}}$$

In the FCOM Flight Planning Chapters the optimum altitude is shown on the Cruise Level chart for 2 or more speeds. This chart also shows the Maximum Altitudes as limited by performance and buffet. A typical FCOM chart showing the variation of optimum altitude with weight for one speed is shown below.

A318/319/320/321 FLIGHT CREW OPERATING MANUAL	FLIGHT PLANNING CRUISE LEVEL	2.05.20 SEQ 205	P 2 REV 26



It should be noted that the influence of airspeed on optimum altitude is not very significant in the range of normal cruise speeds.

In order to minimize fuel burn, the aircraft should therefore be flown at the optimum altitude. However this is not always possible. Performance limitations such as rate of climb or available cruise thrust can lead to a maximum altitude below the optimum, as can buffet limitations. At low weights, the optimum altitude may be above the maximum certificated altitude. In addition, Air Traffic Control restrictions can affect the flown flight level.

The following table shows the specific range penalty of not flying at optimum altitude, assuming a cruise Mach No of 0.8. It should be noted that each airframe/engine combination has different values. It should be noted that these are average values and there are slight variations with different weight/optimum altitude combinations.

Specific Range Penalty for not flying at Optimum Altitude

Aircraft	+2000ft	-2000ft	-4000ft	-6000ft
A300B4-605	2.0%	0.9%	3.4%	9.3%
A310-324	1.9%	1.4%	4.4%	9.3%
A318-111	0.7%	1.6%	5.0%	10.0%
A319-132	1.0%	3.0%	7.2%	12.2%
A320-211	**	1.1%	4.7%	9.5%
A320-232	1.4%	2.1%	6.2%	12.0%
A321-112	2.3%	1.4%	4.6%	15.2%
A330-203	1.8%	1.3%	4.2%	8.4%
A330-343	3.0%	1.0%	3.2%	7.2%
A340-212	1.4%	1.5%	4.0%	8.0%
A340-313E	1.5%	1.6%	5.2%	9.5%
A340-642	1.6%	0.6%	2.2%	5.1%

** Above Maximum Altitude

Generally if one flies within 2000ft of optimum altitude, then the specific range is within about 2% of the maximum. However fuel burn-off is an important consideration.

Consider an A340-313E at a weight such that the optimum altitude is 33000ft. If the aircraft flies at FL 310 the SR penalty is 2.1% for the weight considered. However after a fuel burn of 20800kg, during which the aircraft would have traveled 1400nm the optimum altitude increases to 35000ft and the penalty is now 5.2%.

There is also an effect on block time due to the different altitudes. The true air speed increases/decreases 4kts, or just under 1% for each 2000ft lower/higher cruise altitude.

5.3.2.1 CROSS-OVER ALTITUDE VERSUS OPTIMUM ALTITUDE

It has been previously shown that the TAS is the maximum at the crossover altitude. One can wonder whether it is profitable to stay at this altitude, instead of climbing to the first optimum altitude.

Assuming the standard climb laws, the crossover altitude can be derived. The standard speed laws are tabulated in paragraph 5.2.2.

The next table shows the effect of flying at the crossover altitude instead of optimum flight levels. The 1st optimum flight level has been chosen for the short sectors, whereas longer sectors assume step climbs with FL 310, 350 and 390 being available. This assumes ISA conditions and a take-off weight for a typical sector with max passengers and some freight (2500kg for the A320 family and 5000kg for the other aircraft).

Aircraft type	Sector Distance	Cross-over altitude	Optimum Flight Levels	Gained time (min)	Increase in fuel consumption
A300B4-605R	2000nm	29000 ft	310/350	7	1190kg
A310-324	2000nm	30000ft	350/390	3	2160kg
A318-111	1000nm	29000 ft	370	3	740kg
A319-112	1000nm	29000 ft	370	3	650kg
A320-214	1000nm	29000 ft	350	2	580kg
A320-232	1000nm	29000 ft	340	2	440kg
A321-211	1000nm	29000 ft	330	2	350kg
A330-203	4000nm	31000 ft	350/390	9	5040kg
A330-223	4000nm	31000 ft	350/390	9	5780kg
A330-343	4000nm	31000 ft	350/390	10	6380kg
A340-212	6000nm	29000 ft	310/350/390	17	10900kg
A340-313	6000nm	29000 ft	310/350/390	14	8410kg
A340-313E	6000nm	29000 ft	310/350/390	17	9310kg
A340-500/600	6000nm	29000 ft	310/350/390	18	2430kg

This table shows that flying at crossover altitude increases the fuel burn significantly for a relatively small reduction in block time.

5.3.2.2 CRUISE OPTIMISATION WITH STEPPED CLIMB

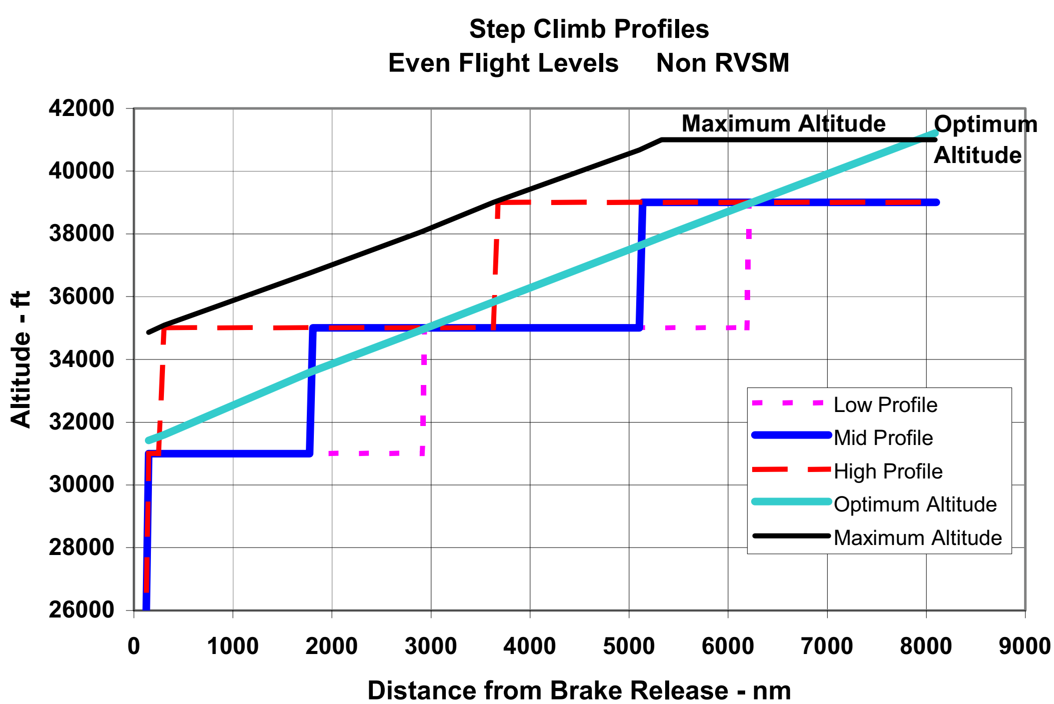
5.3.2.2.1 Introduction

It has been shown that flying at non-optimum altitudes can cause significant fuel penalties, and that the effect of fuel burn is to increase the optimum altitude. The ideal scenario would be to follow the optimum altitude as in the climbing cruise, but A.T.C. constraints, performance and buffet limits do not make this possible. However, by changing the cruise level with step climbs, as the aircraft gets lighter the aircraft will remain as close as possible to the optimum altitude.

5.3.2.2.2 Choice of Profile

Several parameters such as weather conditions, ATC requirements, may influence any decision made by the crew with regard to three fundamental priorities: maneuverability, passenger comfort, and economics.

This pertains to the choice of the cruise flight level that can be made according to the three following climb profiles as shown below for an A340-642:



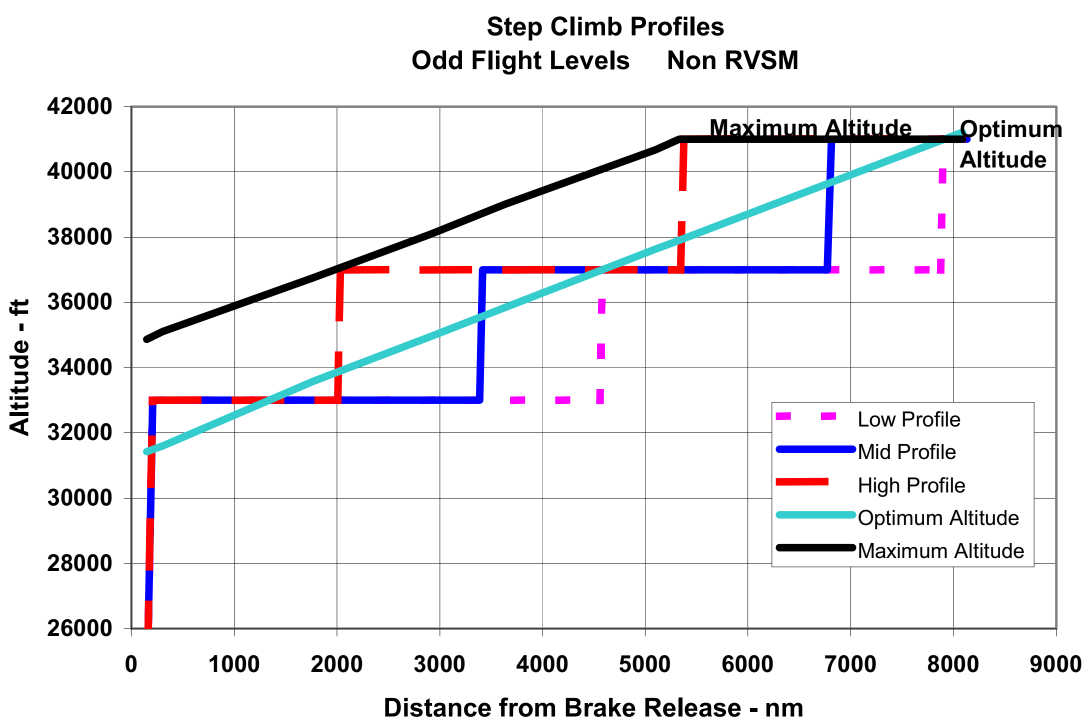
The **Low profile** initiates the step climb at the weight where the next available flight level is also the optimum flight level at that weight. Consequently the flight levels are always at or below the optimum. This has the advantage of better maneuverability margins and generally a better speed as it is closer to the crossover altitude.

The **high profile** initiates the step climb at the weight where the next available flight level is also the maximum flight level at that weight. The flight levels are mainly above the optimum and the aircraft will have decreased maneuverability and fly slower.

The **mid profile** initiates the step climb at the weight where the specific range at the next available flight level is better than that at the current flight level. This enables the flight profile to remain as close as practically possible to the optimum flight level. It is this technique that is recommended for best fuel economy, and is also very close to that required for best economics.

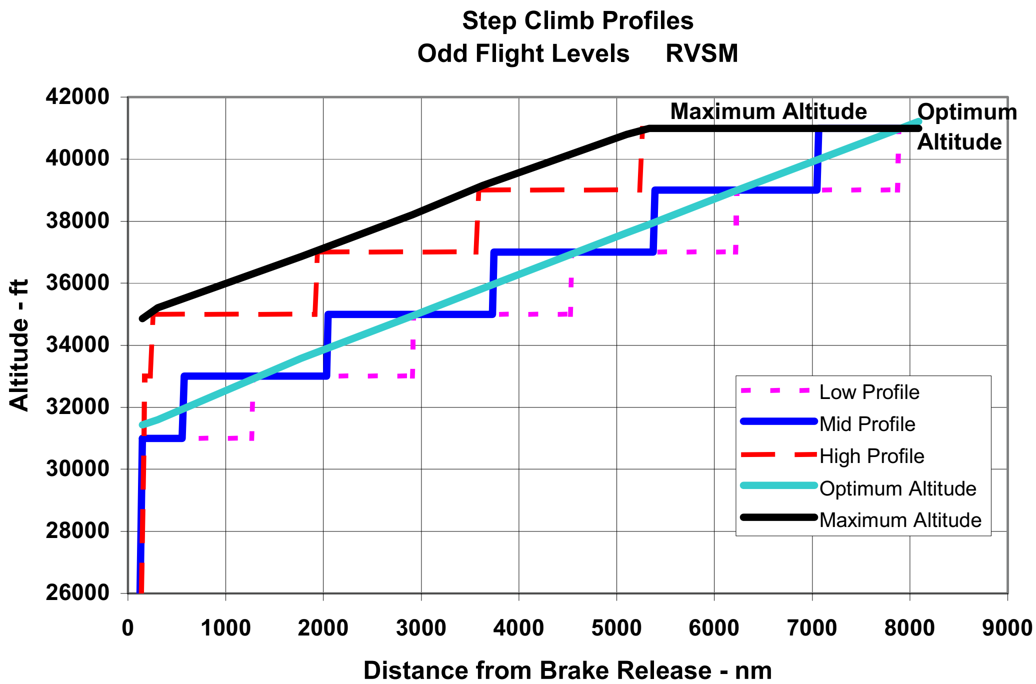
It is interesting to note that, in this case, the Mid profile step climb is made 1140nm before the Low Profile step climb and 1520nm after the High profile step climb.

The situation changes with odd flight levels:



Because of the different available flight levels, the step climbs are initiated some 1500nm further than the even flight level step climb points. However the relative merits of each profile remains the same.

With Reduced Vertical Separation Minima (RVSM) the difference between flight levels reduces from 4000 to 2000ft and this enables the aircraft profile to remain much closer to the optimum. In addition the high profile (depending on the aircraft) remains much higher than the optimum, increasing the fuel penalty. This profile is shown on the following page.



Thus pilots are advised to perform step climbs around the optimum altitudes. To facilitate this, the optimum weight for climb to the next flight level is given in most FCOM's (not A300/A310). An example is shown below.

A318/319/320/321 FLIGHT CREW OPERATING MANUAL	FLIGHT PLANNING	2.05.20	P 1
	CRUISE LEVEL	SEQ 205	REV 31

R **OPTIMUM WEIGHT FOR 4000 FEET STEP CLIMB**

R

STEP CLIMB FROM/TO	WEIGHT (1000 kg/1000 lb)					
	≤ ISA + 10		ISA + 15		ISA + 20	
	LR	M.78	LR	M.78	LR	M.78
310/350	74/163	75/165	74/163	75/165	74/163	75/165
330/370	68/149	68/149	68/149	68/149	67/147	68/149
350/390	61/134	62/136	61/134	62/136	61/134	62/136
370/410	55/121	56/123	55/121	56/123	55/121	56/123

On all Airbus FMS-equipped aircraft, the optimum altitude (OPT FL) and the maximum flight level (MAX FL) are displayed on the MCDU progress page. The recommended maximum altitude in the FMGC ensures a 0.3g buffet margin, a minimum rate of climb of 300ft/min at MAX CLIMB thrust and a level flight at MAX CRUISE thrust. Depending on weight and type, it is 2000 to 4000ft above the optimum altitude.

Typical cruise distances between 2000 foot altitude steps are shown in the following table:

Type	Distance - nm
A300	1000 - 1100
A310	1150 - 1250
A320	1200 - 1300
A330	1500 - 1650
A340	1500 - 1650
A340-500/600	1600 - 1700

For sector lengths greater than these, where ATC restrictions do not allow a change in cruise altitude from the initial requested level, the initial request should be the highest compatible with the maximum cruise altitude.

5.3.2.3 DELAYS IN ALTITUDE CHANGES

Let's consider an aircraft that is at flight level 330, which has, at that weight, an optimum flight level of 370. If it does not climb to FL 370 for ATC or other reasons, it will consume more fuel. The following table shows the difference in fuel burn for a 500nm still air cruise, when cruising at FL 330 instead of FL 370.

Aircraft Type	Fuel Increase (kg)	Fuel Increase (%)
A300B4-605R	238	5.2
A310-324	221	5.3
A318-111	150	6.2
A319-132	184	7.9
A320-211	158	6.2
A320-232	187	7.9
A321-112	155	5.5
A330-203	324	5.5
A330-343	342	5.6
A340-212	393	6.2
A340-313E	378	6.0
A340-500/600	336	4.1

Thus delaying a climb to a higher altitude has a significant impact on fuel burn.

5.3.2.4 OPTIMUM ALTITUDES ON SHORT STAGES

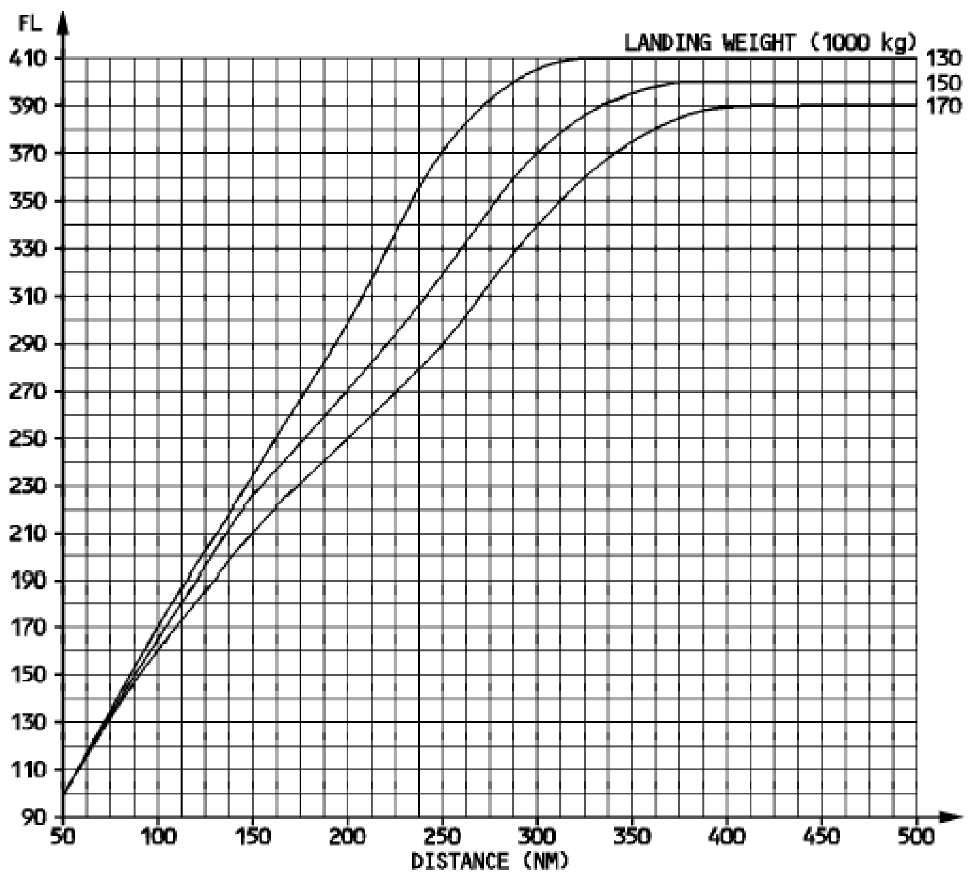
For short stages, the choice of cruise flight level is often restricted due to the necessary climb and descent distance. Airbus philosophy assumes a minimum 5 minute cruise sector, because a climb followed immediately by the descent is not appreciated by pilots, passengers or ATC.

If the stage length is of sufficient length that the optimum flight level can be reached, but the cruise is of short duration, then the benefits at this flight level will be marginal. It may even be worthwhile to cruise at one flight level lower, as the increased climb consumption offsets any reduced cruise consumption.

In the FCOM there is a chart showing the optimum altitude on a short stage. An example is shown below.

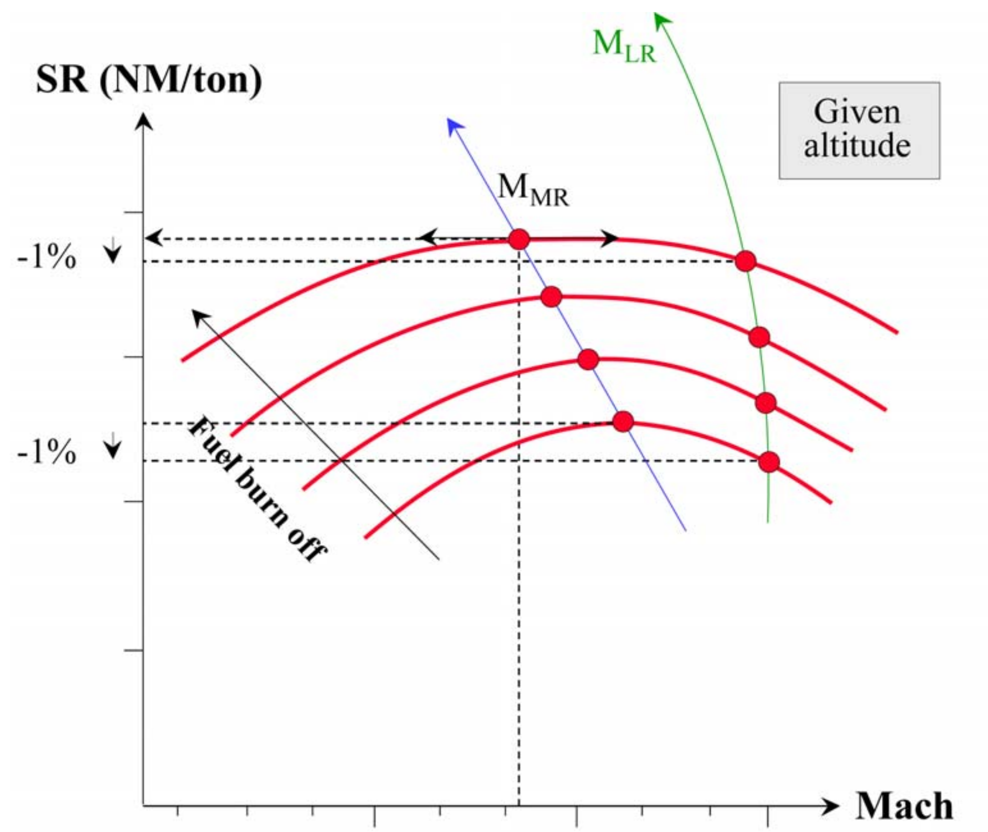
A330 FLIGHT CREW OPERATING MANUAL	FLIGHT PLANNING	2.05.20	P 4
	CRUISE LEVEL	SEQ 070	REV 06

OPTIMUM ALTITUDE ON SHORT STAGE



5.3.3 CRUISE SPEED OPTIMISATION

Having been given a flight level which may be a requested optimum altitude or one imposed by air traffic control, speed is the only remaining parameter that requires selection. The following picture shows the variation of Specific Range with Mach Number for different aircraft weights at a fixed altitude.

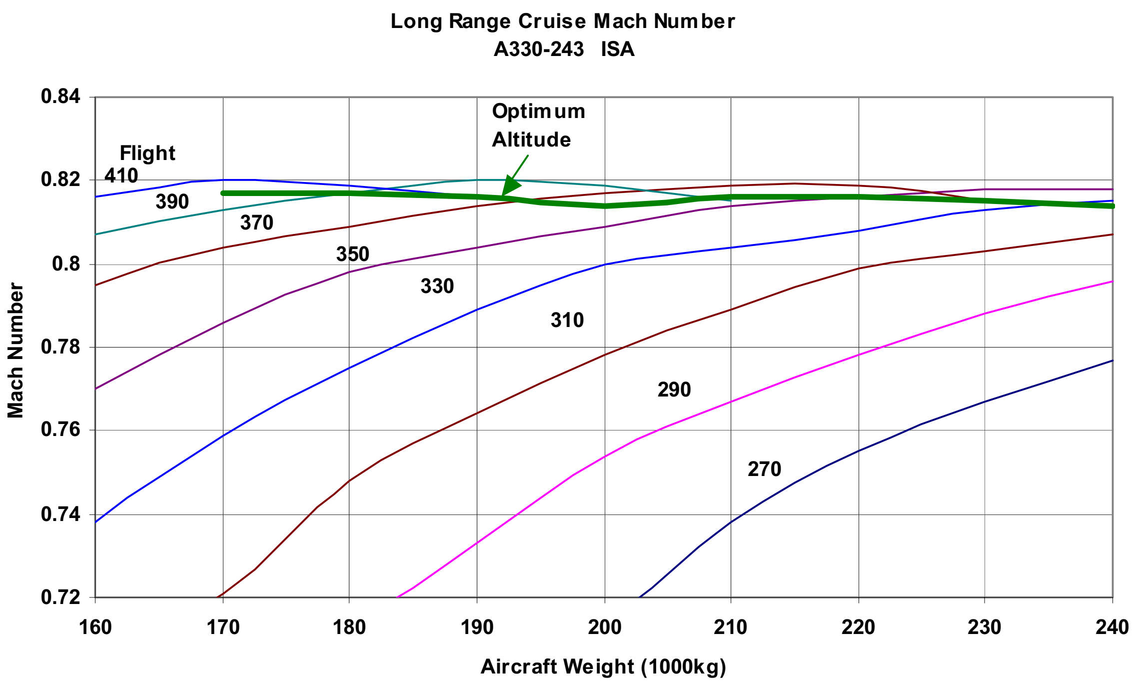


The Mach number, which gives the best specific range, can be determined. It is called the maximum range cruise Mach (M_{MR}). Nevertheless, for practical operations, a long-range cruise procedure is defined which gains a significant increase in speed compared to M_{MR} with only a 1% loss in specific range. Like the M_{MR} speed, the M_{LRC} speed also decreases with decreasing weight, at constant altitude.

A more detailed explanation of this can be found in "Getting to Grips with Aircraft Performance"

The following chart shows the typical variation of the Long Range Cruise Mach Number with aircraft weight for various flight levels. Also plotted on this chart is the optimum altitude line. This shows that there is not much variation in the long-range cruise mach number at these altitudes.

It would therefore be possible to fly a constant Mach number procedure instead of the variable LRC speed procedure. In order to save fuel however, the exact LRC speed should be maintained.

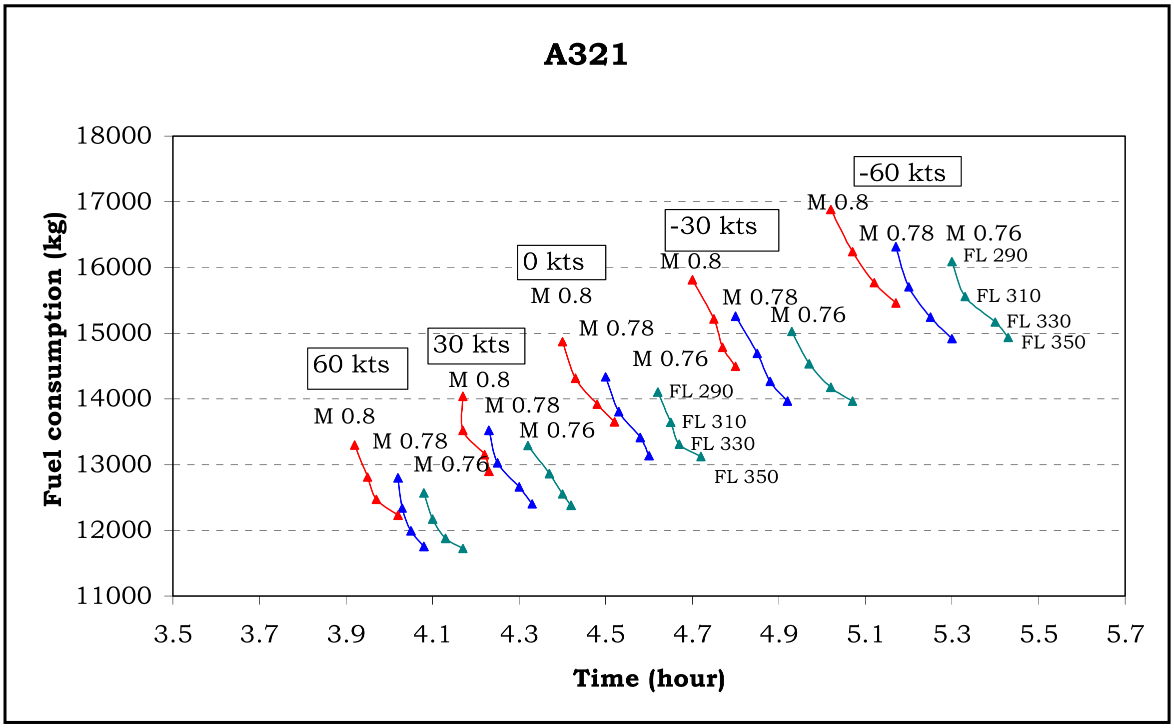


The Long Range Cruise Speed can be found in the Cruise tables in the FCOM.

5.3.4 WIND INFLUENCE

Wind can have a significant influence on fuel burns. Nowadays, meteorological forecasts are very reliable and its integration into the FMS provides accurate information to crews. Hence the latter best perform flight planning with a view towards fuel savings.

The effect of the wind on trip time and fuel is shown on the following chart, which gives fuel consumption and time for a 2000nm sector, with respect to flight levels, Mach number and wind (tailwind positive) for a fixed take-off weight.

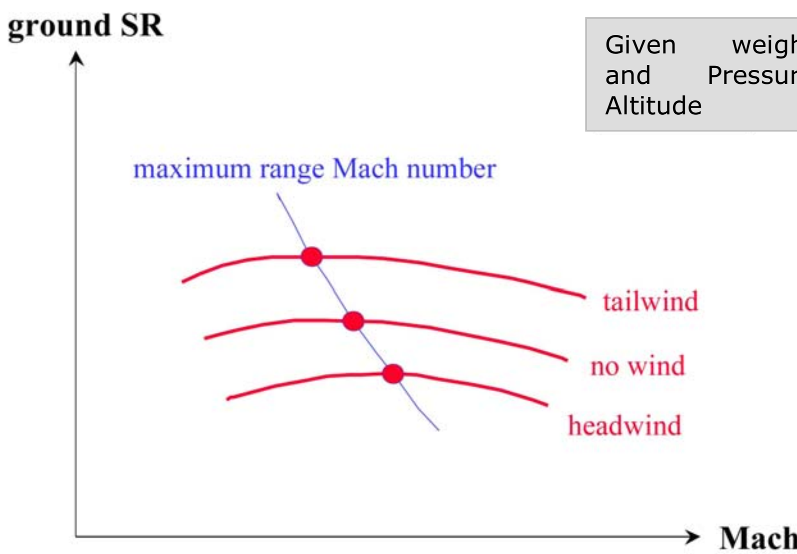


This plot graphically shows the magnitude of the significant changes in fuel consumption and time due to winds. FCOM Tables show the equivalent still air distances for any ground distance/wind combination.

However the winds can affect the performance optimization as well as changing the effective still air distance. The M_{MR} (or M_{LRC}) value varies with headwind or tailwind, due to changes in the SR.

The effect of a tailwind is to increase the ground speed, and therefore the SR, by the ratio of ground speed to airspeed. A given wind speed therefore has a larger effect at the lower airspeeds, which changes the optimum speed.

The following chart shows the Maximum Range Mach number versus wind variations.



M_{MR} and wind influence

This shows that

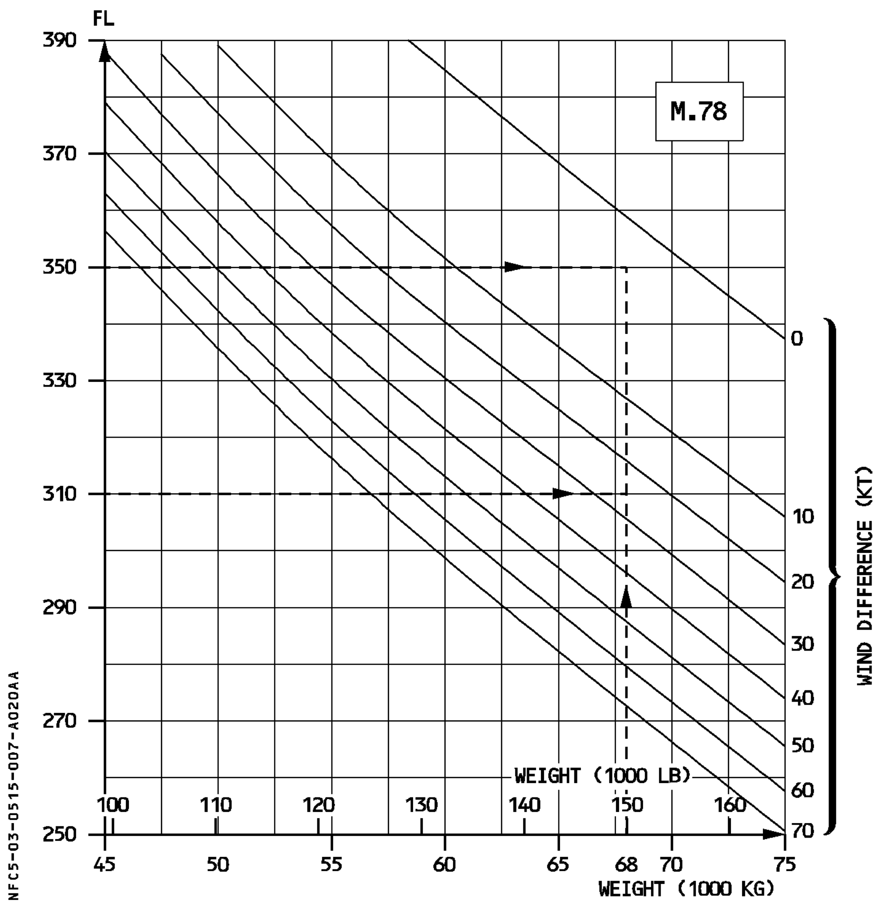
Tailwinds increase the specific range and lower the speeds
Headwinds decrease the specific range and raise the speeds.

The wind speed can be different at different altitudes. For a given weight, when cruise altitude is lower than optimum altitude, the specific range decreases. Nevertheless, it is possible that, at a lower altitude with a favorable wind, the ground specific range improves. When the favorable wind difference between the optimum altitude and a lower one reaches a certain value, the ground-specific range at lower altitude is higher than the ground-specific range at optimum altitude. As a result, in such conditions, it is more economical to cruise at the lower altitude.

There is information in the most FCOM's (not A300/310) to indicate the amount of favorable wind, necessary to obtain the same ground-specific range at altitudes different from the optimum. If the wind is more favorable then it is beneficial to fly lower. The following shows such a page:

A319/320/321 FLIGHT CREW OPERATING MANUAL	IN FLIGHT PERFORMANCE CRUISE	3.05.15 P 7	
		SEQ 020	REV 24

WIND ALTITUDE TRADE FOR CONSTANT SPECIFIC RANGE



GIVEN : Weight : 68000 kg (150 000 lb)
Wind at FL350 : 10 kt head

FIND : Minimum wind difference to descend to FL310 : (26 − 3) = 23 kt

RESULTS : Descent to FL310 may be considered provided the tail wind at this altitude is more than (23 − 10) = 13 kt.

5.3.5 MANAGED MODE

The flight management system (FMS) optimizes the flight plan for winds, operating costs and suggests the most economical cruise altitude and airspeed, depending on the cost index chosen by the airline. An airline that wants to save fuel has to choose a low cost index. The next part intends to highlight the impact of the cost index on fuel consumption and on trip time. More complete information can be found in the "Getting to Grips with Cost Index" brochure.

5.3.5.1 ECONOMIC MACH NUMBER

Long-range Cruise Mach number was considered as a minimum fuel regime. If we consider the Direct Operating Cost instead, the **Economic Mach number** (**M_{ECON}**), can be introduced.

Direct Operating Costs (DOC) are made up of fixed, flight-time related and fuel-consumption related costs. As a result, for a given trip, DOC can be expressed as:

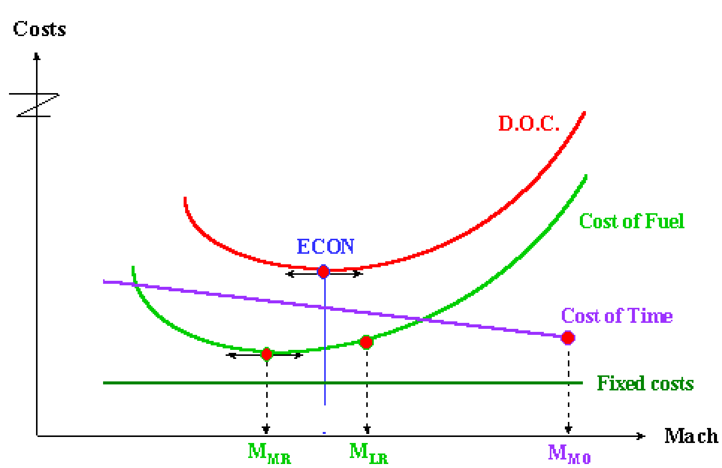
$$\boxed{DOC = C_C + C_F.\Delta F + C_T.\Delta T}$$

where C_C = fixed costs

C_F = cost of fuel unit ΔF = trip fuel

C_T = time related costs per flight hour ΔT = trip time

As DOCs are calculated per nautical mile, it is possible to plot fuel-related costs, flight-time related costs, and direct operating costs based on Mach number .



Minimum fuel costs correspond to the Maximum Range Mach number. The minimum DOC corresponds to a specific Mach number, referred to as Econ Mach (M_{ECON}).

$$\begin{array}{llll} FL = \text{constant} & \text{weight} \searrow & \Rightarrow M_{ECON} & \searrow \\ \text{weight} = \text{constant} & \text{FL} \nearrow & \Rightarrow M_{ECON} & \nearrow \end{array}$$

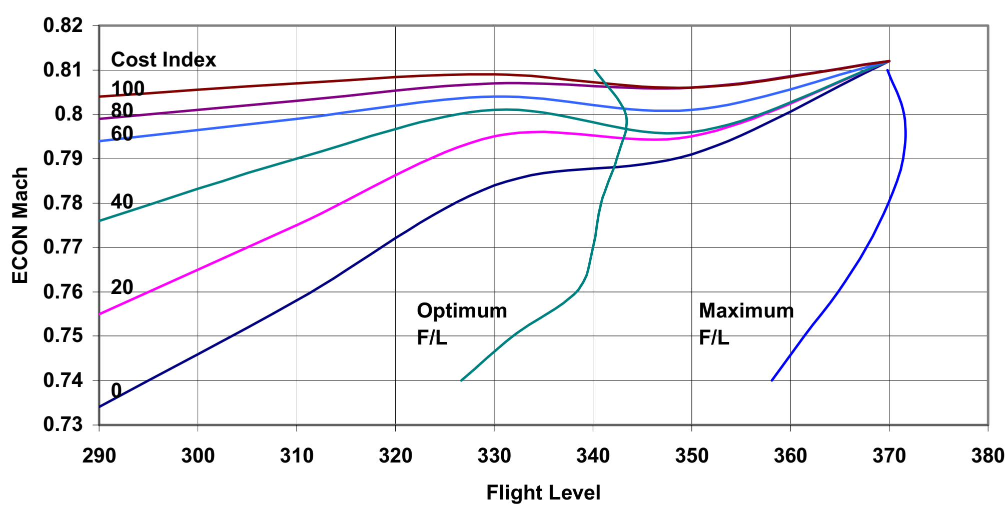
The M_{ECON} value depends on the time and fuel cost ratio. This ratio is called **cost index** (**CI**), and is usually expressed in kg/min or 100lb/h:

$$\text{Cost Index (CI)} = \frac{\text{Cost of time}}{\text{Cost of fuel}} = \frac{C_T}{C_F}$$

Depending on the cost index, the predicted aircraft and atmospheric conditions, the optimum altitude and the economic Mach number are computed. From then on, fuel consumption depends only of the chosen cost index.

The following chart shows the economic Mach number variation with flight level for different cost indices.

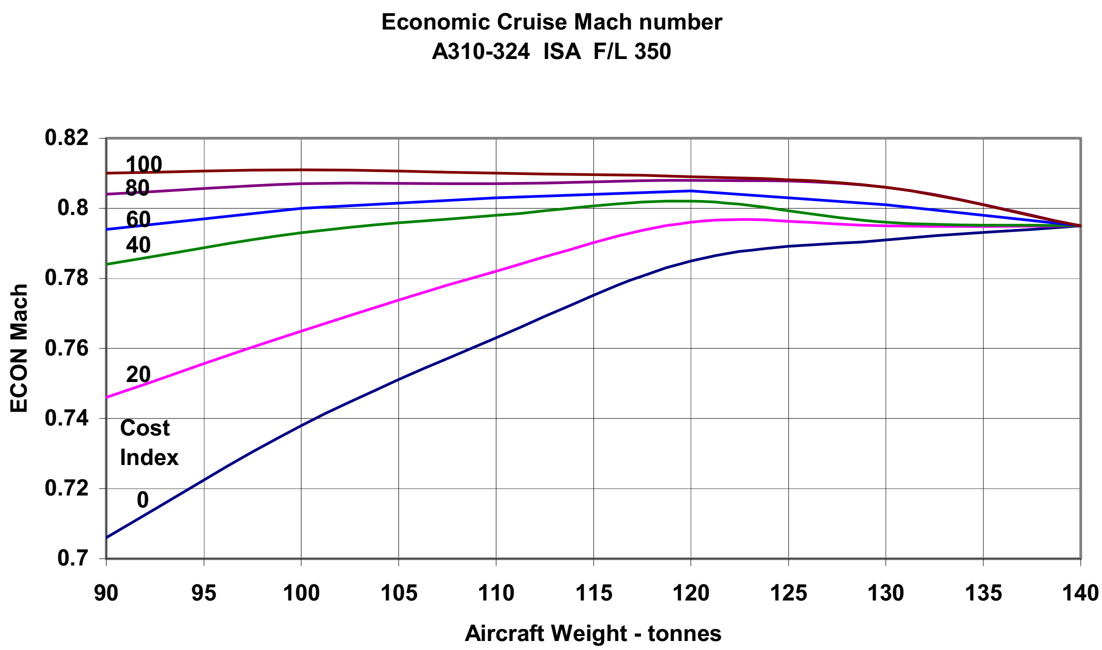
Economic Cruise Mach Number
A310-324 ISA 130000kg



This shows the general trend, common with all aircraft, of increasing economic Mach number with flight level.

The charts also show large economic Mach number changes with flight level for low cost indices, whereas it is rather constant for high cost indices. The economic Mach is very sensitive to the cost index when flying below the optimum altitude.

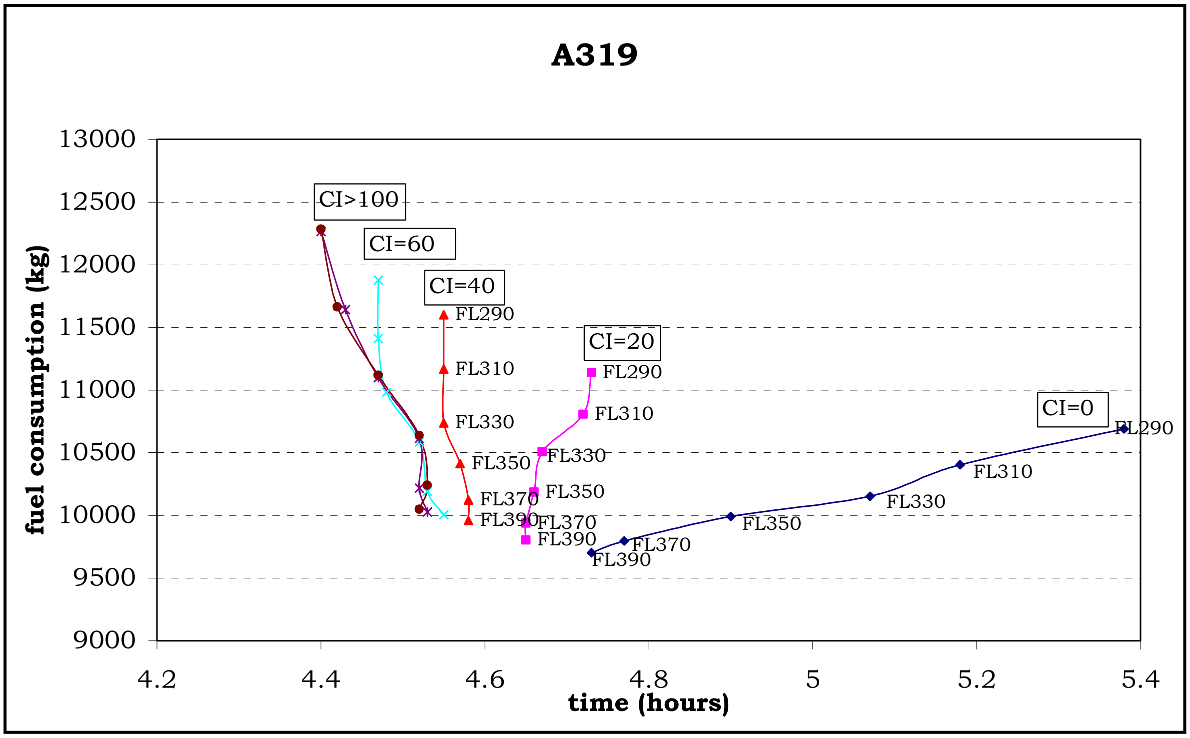
The effect of weight variation at a fixed flight level is shown below.



The charts show that for high cost indices, the economic Mach number stays fairly constant throughout the flight. Nevertheless, for a low cost index, the economic Mach number reduces significantly as the weight reduces. This is quite normal as low cost indices favor fuel consumption at the expense of time. Moreover, we notice that for low cost indices, a small cost index increment has a far-reaching influence on the economic Mach number, and hence on flight time. These trends are typical of all aircraft.

5.3.5.2 TIME/FUEL RELATIONSHIP

To know whether the fuel economies at low cost indices are worthwhile, the impact of cost index on time has to be considered. The following graph show both trip fuel and time for different flight levels and cost indices. The shape of this chart is typical of all types.



As it can be seen, it is not really advantageous to fly at very low cost indices as fuel savings are not significant compared to time loss. Although using slightly higher fuel, a slightly higher cost index gives significant time gains.

For instance, for the A319, increasing the cost index from 0 to 20 reduces the block time by 15 minutes (5%) for a fuel burn increase of only 200kg (2%) on a 2000nm sector.

5.3.6 EFFECT OF SPEED INCREASE ON MANAGED MODE

Flying at a given cost index rather than at a given Mach number provides the added advantage of always benefiting from the optimum Mach number as a function of aircraft gross weight, flight level and head/tailwind components.

This means the ECON mode ("managed" mode) can save fuel relative to fixed Mach schedules ("selected" mode) and for an equivalent time.

One can wonder whether selecting a higher Mach number than the one chosen by the FMS has a significant impact on fuel consumption. Imagine an aircraft flying at flight level 370, in managed mode and at the optimum weight of FL370. The FMS computes the optimum speed based on cost index, temperature and wind. If the pilot selects another (higher) Mach number, the fuel consumption will increase.

The following tables show the effect of such a speed increase.

		Economic Mach No + 0.005			Economic Mach No + 0.01		
		Fuel Penalty		ΔTime	Fuel Penalty		ΔTime
Aircraft	Sector	Kg	%	Min	Kg	%	Min
A300-605	2000 Nm	110	0.4	1	230	0.9	3
A310-324	2000 Nm	90	0.4	1	430	2.0	8
A318	1000 Nm	30	0.5	1	60	1.0	1
A319	1000 Nm	20	0.2	1	40	0.6	2
A320	1000 Nm	20	0.3	1	40	0.7	2
A321	1000 Nm	10	0.1	1	30	0.4	1
A330	4000 Nm	150	0.3	3	330	0.6	6
A340-212	6000 Nm	390	0.5	5	790	0.9	10
A340-313E	6000 Nm	380	0.4	5	900	1.0	10
A340-500	6000 Nm	1050	0.9	5	2540	2.1	9
A340-600	6000 Nm	820	0.7	4	2060	1.8	9

We notice that although decreasing block times, the increase of Mach number above the Optimum speed can result in significant increases in fuel burn. Pilots hence have to be patient and should not change the Mach number even when under the impression that the aircraft does not fly fast enough.

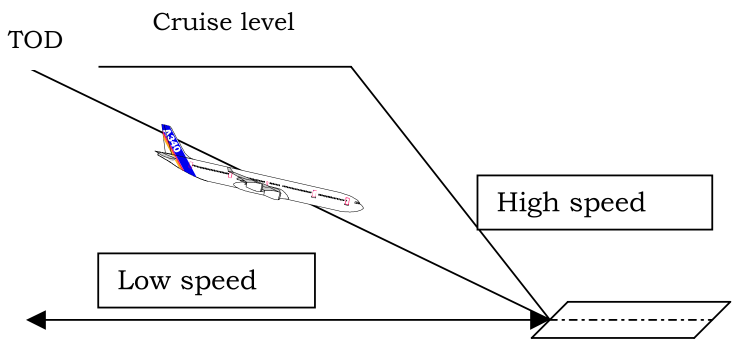
Moreover, when possible, the managed mode must be kept.

5.4 DESCENT

5.4.1 INTRODUCTION

Depending on the descent law, flight paths do vary in steepness.

Indeed, the higher the speed law, the steeper the flight path.



Descent profiles.

Descents are normally performed in three phases on a constant IAS/Mach descent speed schedule, as follows:

- Constant Mach number is maintained until the crossover altitude
- Constant indicated air speed is maintained down to 10000ft
- 250 KT indicated air speed (IAS) is maintained below flight level 100, until the aircraft decelerates for landing

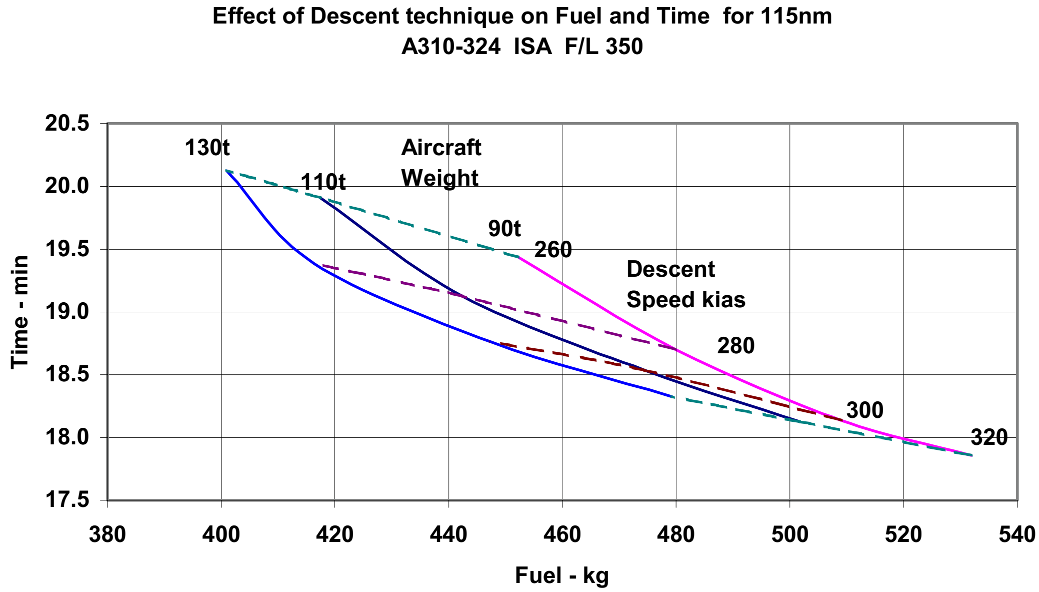
The engine thrust is normally set to flight idle for the descent and the speed is controlled by the aircraft attitude. In these conditions higher weights increase the descent distance because of the reduction of descent gradient (which equals [thrust-drag]/weight in stabilized flight). This also increases the descent fuel.

However a descent from high altitudes at low weight may lead to a gradient of descent that results in an excessive cabin rate of descent. In these cases the rate of descent is reduced by application of power, until a flight idle descent can be continued. This results in what is known as the re- pressurization segment, and this can reverse the weight-descent distance relationship.

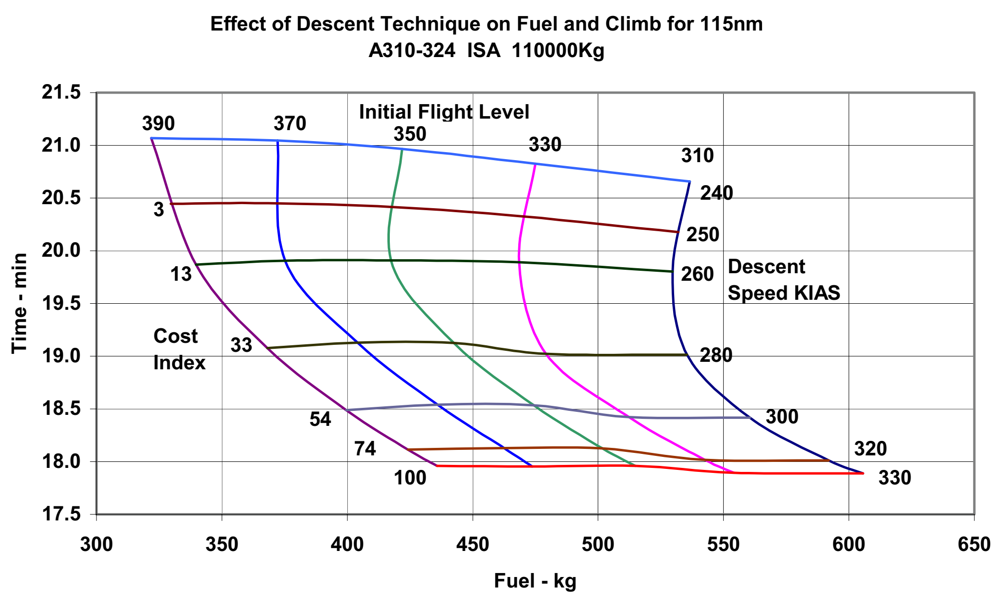
To correctly evaluate the effects of descent techniques, cruise and descent flight must be viewed in relation to each other. A short descent distance for example extends the cruise distance. One has therefore to consider in addition to the descent, a small portion of the cruise to the same distance.

5.4.2 THE EFFECT OF DESCENT TECHNIQUES ON FUEL BURN

An evaluation has been made of the fuel burn to a constant distance, and this now shows that the higher weights use less fuel. Lower speeds, although requiring more fuel for the descent only requires less total fuel because of the longer descent distance. This is shown in the following chart.



At a fixed weight, the following chart shows that the minimum fuel occurs at a descent speed of 240kias to 280kias, dependant on flight level.



However there is a significant time penalty at these speeds.

Note that the effect of the descent Mach number is very dependant on cruise flight level and descent speed, but is relatively small compared to the descent speed effect, and is not fully investigated here.

These descent charts are typical of the other Airbus aircraft. Generally they show a minimum fuel speed of 260 to 280 kts for flight level 310, reducing to 240kts for flight level 390. The exceptions are the A318, A319, A320 and A330, which show the minimum fuel at 240kias for all flight levels which is slightly lower than the other aircraft at FL310.

Appendix B presents some examples of these descent charts for other Airbus aircraft.

The following tables show, for various Airbus aircraft, the descent time and fuel variations for a fixed distance, from FL 350, relative to a 300kias reference speed.

Type	∆Fuel – kg					
	240KT	260 KT	280 KT	300 KT	320 KT	330/340KT *
A300	-55	-60	-30	0	25	35
A310	-55	-60	-30	0	25	40
A318, 319, 320	-50	-40	-20	0	20	25
A321	-35	-40	-20	0	20	35
A330	-110	-105	-60	0	50	70
A340–200/300	-70	-90	-50	0	50	75
A340-500/600	-125	-130	-70	0	70	100

Type	∆Time – minutes					
	240 KT	260 KT	280 KT	300 KT	320 KT	330/340KT *
A300	2.7	1.5	0.6	0	-0.4	-0.6
A310	2.4	1.4	0.6	0	-0.4	-0.6
A320 family	2.6	1.4	0.6	0	-0.4	-0.6
A330	3.5	2.0	0.8	0	-0.6	-0.8
A340–200/300	3.2	1.8	0.8	0	-0.6	-0.8
A340-500/600	3.3	1.9	0.8	0	-0.6	-0.8

* A300/A310/A320 330kias A330/A340 340kias

Comparing these tables to the equivalent climb comparison tables in chapter 5.2.4, it can be noticed that descent techniques often have a greater effect on fuel and time than climb techniques.

5.4.3 MANAGED MODE DESCENT

The FMS computes the Top Of Descent (TOD) as a function of the cost index. We notice that the higher the cost index:

The steeper the descent path (the higher the speed)

The shorter the descent distance

The later the top of descent.

Descent performance is a function of the cost index; the higher the cost index, the higher the descent speed. But contrary to climb, the aircraft gross weight and the top of descent flight level appear to have a negligible effect on the descent speed computation.

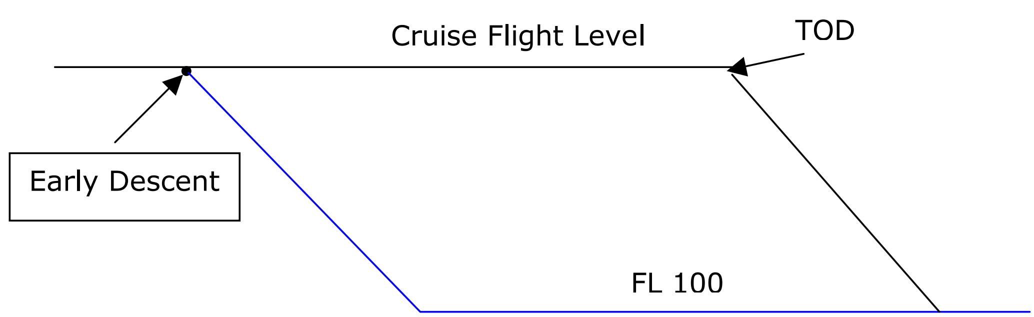
It can be noticed that time to descent is more dependant on cost indices than the time to climb.

On the Effect of Descent Technique on Fuel and Time chart, the cost index has been annotated for each speed. It can be seen that the minimum fuel is at a CI of 0, and the minimum time occurs with a high CI, as would be expected.

For the A300, A310 and A320 family the speed at zero cost index is about 250kias. For the A330/340 it is about 270kias. Max speed normally corresponds with a high cost index of 60 to 120. Once more it can be seen how, in the managed mode, the cost index is used to choose the balance between fuel burn and flight time.

5.4.4 EARLY DESCENT

If the aircraft begins its descent too early, the aircraft would leave its optimal flight level, where fuel consumption is at its best, and would have to cruise at a lower altitude to arrive at the same point.



Two descent situations were simulated:

• Descent commenced 15nm (or about 2 minutes) early followed by a level-off at FL100.

• Cruise continued from the early descent point until the optimum start of descent, followed by the descent

At 10000ft, the cruise speed could be selected between LRC and max speed. If in managed mode, one could continue at the same cost index, or select the 250kias below 10000ft limiting speed. The following table compares the two options.

Aircraft	250KIAS at FL100		LRC at FL100	
	∆Fuel – kg	∆Time – min	∆Fuel – kg	∆Time – min
A300-600	70	1.1	95	0.4
A310	70	1.1	90	0.3
A320 family	50	1.1	65	0.2
A330	80	1.2	100	0.5
A340-200/300	95	1.2	105	0.5
A340-500/600	135	1.2	125	0.5

Cruising faster at 10000ft reduces the time penalty at the expense of fuel.

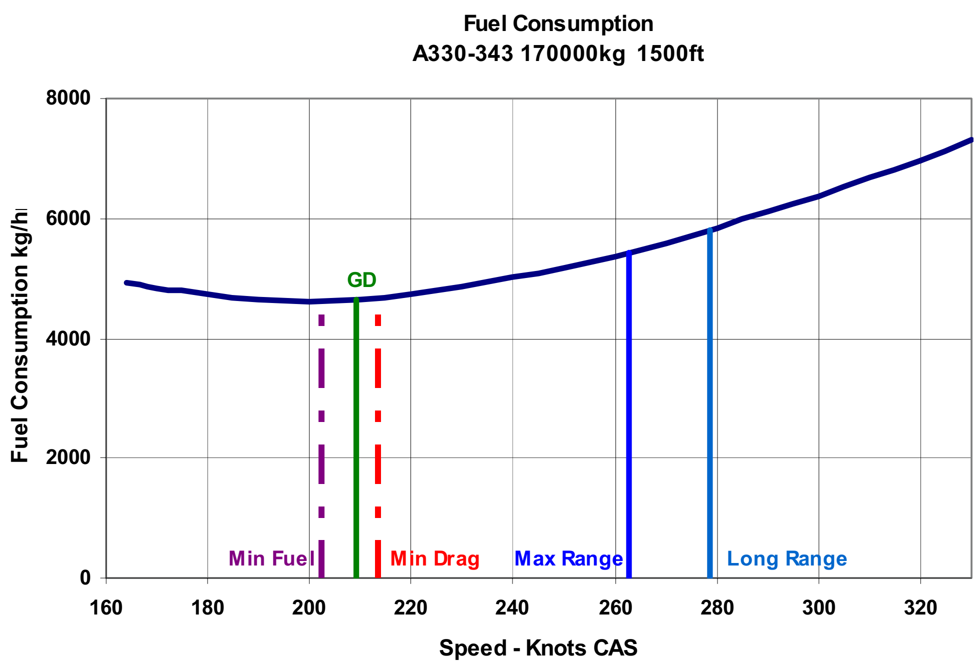
After a long flight with an A340–500 or –600, starting the descent some 100nm early would not appear to be significant in the overall flight. However this can result in a 900kg fuel burn increase and 8 minutes longer block time.

5.5 HOLDING

5.5.1 INTRODUCTION

When holding is required, it is generally flown on a "race track pattern", composed of two straight legs plus two 180 degree turns. In a hold the distance covered is not the primary objective. On the contrary, the knowledge of the maximum holding time (maximum endurance) is a determining factor for any diversion decision. As a result, it is important, during holding, to try to minimize fuel by simply minimizing fuel flow.

For all aircraft, the minimum fuel consumption speed is very close to the maximum lift-to-drag ratio (Green Dot) speed as shown below. As a result, in clean configuration, the standard holding speed is selected equal to **green dot** speed (GD).



Holding patterns may be quite limiting around certain airports due to obstacle proximity. Therefore, green dot is sometimes too high, especially during turn phases where the bank angle can be too significant. As it is not possible to significantly reduce the speed below green dot in clean configuration, slats may be extended and a holding done in **CONF1** at "**S**" speed. (min slat retraction speed Conf 1 to Conf clean).

At other airports, Air Traffic Control may require the hold to be performed at a certain speed, and it may not be possible fully optimise the fuel burn. In order to allow flexibility in planning and operations, the FCOM has four different holding speed and configuration combinations, adapted to each type of aircraft.

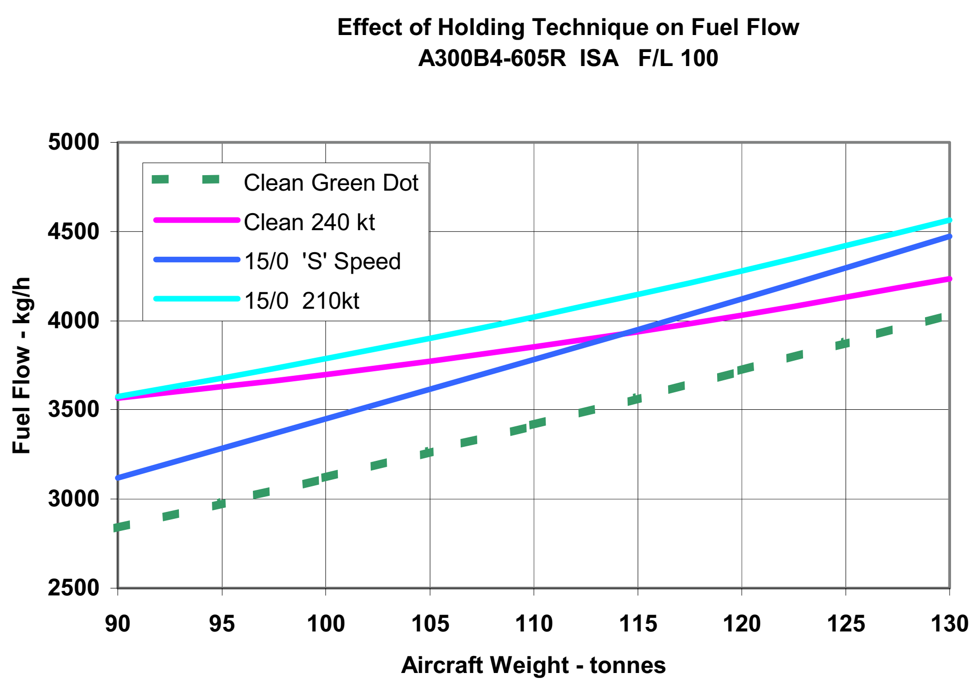
The following table gives the configurations and speeds for each type.

Aircraft types	First Flap/slat Configuration		Clean configuration	
A300-600	210kts	S speed	240kts	Green Dot
A310	170kts	S speed	210kts	Green Dot
A320 Family (CFM)	170kts	S speed	210kts	Green Dot
A320 Family (IAE)	170kts	S speed	210kts	Green Dot + 20
A330	170kts	S speed	210kts	Green Dot
A340-200/300	210kts	S speed	240kts	Green Dot
A340-500/600	240kts	S speed	-	Green Dot

For the A300/A310 the first configuration is flap 15, slat 0. For the other aircraft this is Conf 1. Note that the fourth combination for the A340-500/600 is Configuration 2 at 210kts.

5.5.2 VARIOUS CONFIGURATION / SPEED COMBINATIONS

The following graphs show the holding fuel flow variation with weight for the four different holding configurations. This is done at an altitude of 10000ft.

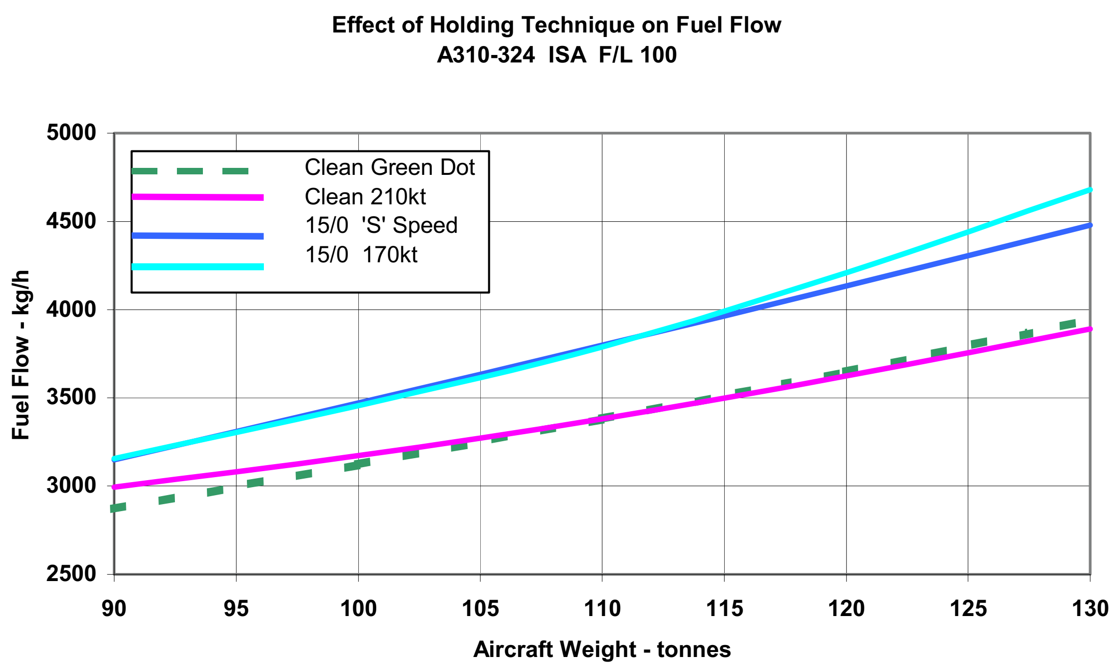


This graph is for an **A300** and it shows the advantage of holding in a clean configuration at the green dot speed. The clean configuration fixed speed of 240kt is significantly higher than the green dot speed; hence the large increase in fuel flow with this technique. The 15/0 configuration with a fixed speed of 210kt is also significantly higher than the 'S' speed, hence higher fuel flows.

The large variation in fuel flow shows how important it is to use the right configuration and speed, compatible with the other operational requirements.

The **A340-200/300** schedules the same hold speeds as the A300, and the graphs have a similar form with a large increase in fuel flow at low weights with the fixed speed techniques. However at high weights the difference is much smaller. There is also a large increase when using Conf 1. Once more holding clean at green dot speed gives the lowest fuel flow.

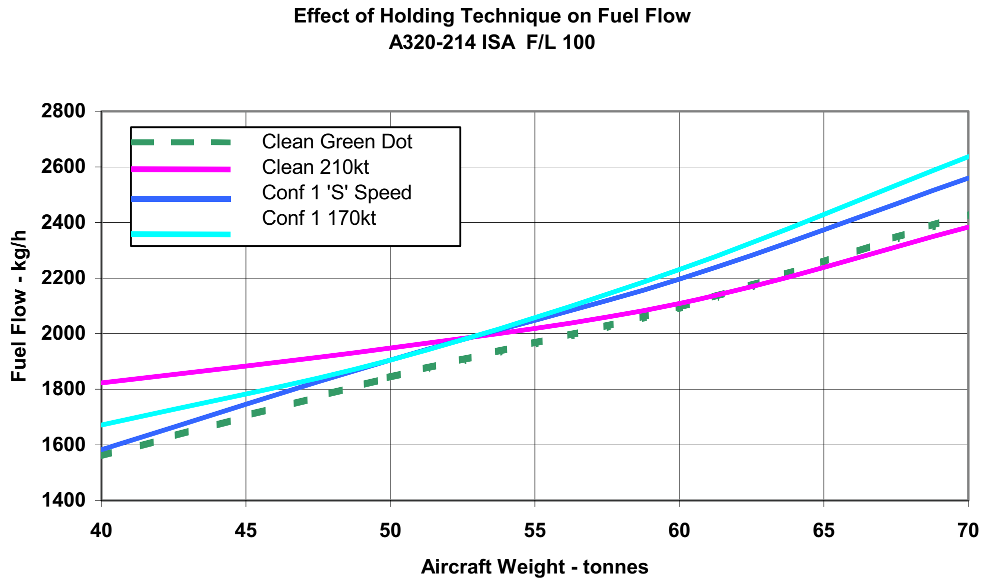
The following graph is for the **A310** and this shows completely different characteristics because of the lower fixed speeds used in each configuration.



Each configuration shows very similar fuel flow, whichever speed technique is used. The clean configuration green dot speed still represents the best single choice for lowest fuel burn over the normal holding weight range.

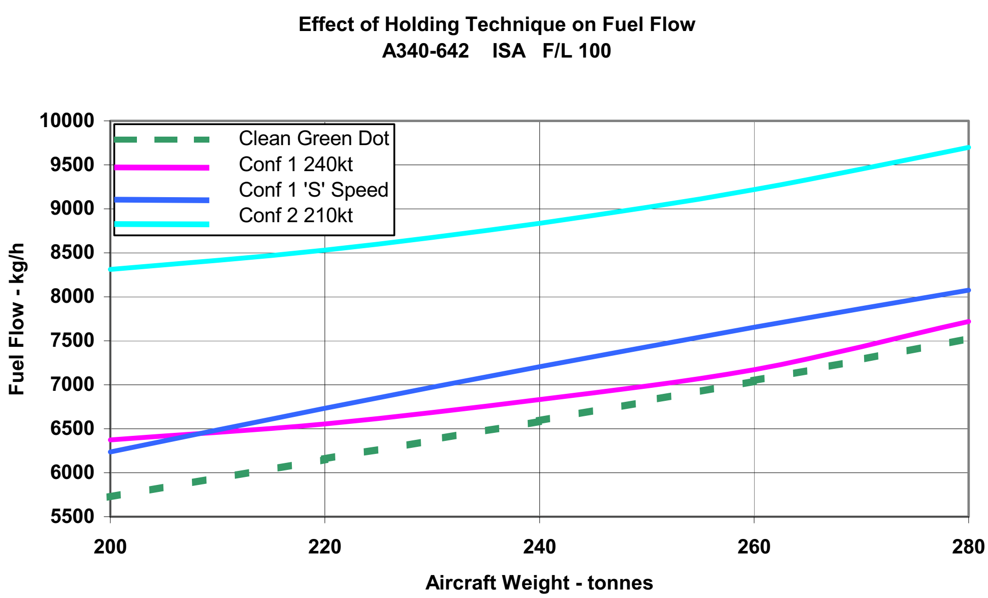
The **A330**, which has the same hold speed schedules shows the same characteristics, with clean configuration at green dot speed being marginally better than clean configuration at 210kt over the normal holding weight range.

The **A320** family shows a completely different set of characteristics as shown in the graph on the next page.



The variation of different techniques is very weight sensitive. However it is still the clean configuration at green dot speed that gives the lowest fuel flow. This picture is typical of all the A320 family.

Finally the **A340-500/600** has another set of configuration/speed combinations and the following graph shows its different characteristics, but the basic concept that the clean configuration and green dot is the best combination still remains true.



There is also **altitude** to be considered, although it is often not the operator's decision what flight level to hold at. Altitude has different effects on the fuel flow, depending on the airframe/engine combination. However, whatever the altitude effect, it generally affects all techniques equally; generally the higher the hold altitude the lower the fuel flow. This however is true only up to a certain altitude and this varies with each type.

The following table shows this altitude effect for a hold in the clean configuration at green dot speed. The holding fuel flow is compared with the lowest for the flight levels considered for each type, and the difference expressed as a percentage.

Flight Level	50	100	150	200	250	300	350	400
A300B4-605R	4	2	1	0	3	8	16	
A310-324	11	5	2	0	0	5	9	23
A318-111	13	8	4	2	1	0	0	5
A319-112	19	11	3	1	0	1	0	4
A320-214	13	5	3	1	1	1	0	2
A320-232	7	5	5	5	2	0	4	11
A321-211	14	11	8	3	0	1	5	
A330-203	2	1	0	0	2	4	8	18
A330-223	9	9	5	2	0	1	6	14
A340-343	10	5	1	0	0	2	7	16
A340-212	3	2	0	0	2	3	5	
A340-313E	2	1	0	0	2	3	5	
A340-642	6	2	0	1	2	3	4	11

In order to allow an assessment of the sensitivity of each aircraft type to different hold techniques, the following table shows the **extra fuel** required to hold for 15 minutes at 10000ft in the first flap configuration at 'S' speed, compared to Conf clean at green dot speed.

Effect of Holding in First flap Setting at 'S' speed compared with Clean at Green Dot speed

Aircraft types	Fuel Increase (kg) Low Holding Weight	Fuel Increase (kg) High Holding Weight
A300B4-605R	70	110
A300B4-622R	110	190
A310-324	70	135
A318	5	10
A319	10	30
A320	10	30
A321	30	50
A330-203	135	175
A330-223	175	205
A330-343	145	175
A340-212	170	230
A340-313	125	175
A340-642	130	150

The table shows that the green dot speed/clean configuration combination enables significant savings to be made.

However, green dot speed increases with weight and can become higher than the maximum recommended speeds, which are listed below:

Levels	ICAO	PAN-OPS	FAA	France
Up to 6,000 ft inclusive	230 KT	210 KT	200 KT	220 KT
Above 6,000 ft to 14,000 ft inclusive	230 KT	230 KT	230 KT	220 KT
Above 14,000 ft to 20,000 ft inclusive	240 KT	240 KT	265 KT	240 KT
Above 20,000 ft to 24,000 ft inclusive	265 KT	240 KT	265 KT	240 KT
Above 24,000 ft to 34,000 ft inclusive	265 KT	240 KT	265 KT	265 KT
Above 34,000 ft	M 0.83	240 KT	265 KT	M 0.83

If green dot is higher than these maximum recommended speeds, it is advised to hold in configuration 1 at "S" speed below 20000ft: keeping clean configuration coupled with a speed reduction would save fuel but would decrease the speed margins which are especially important in turbulent conditions.

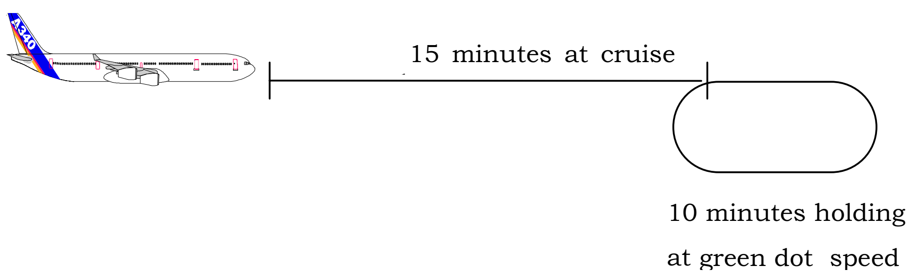
5.5.3 LINEAR HOLDING

If holding is going to be necessary, linear holding at cruise flight level and at green dot speed should be performed whenever possible since total flight time will remain constant (cruise time is increased but holding time is reduced) and fuel flow is lower at high flight levels.

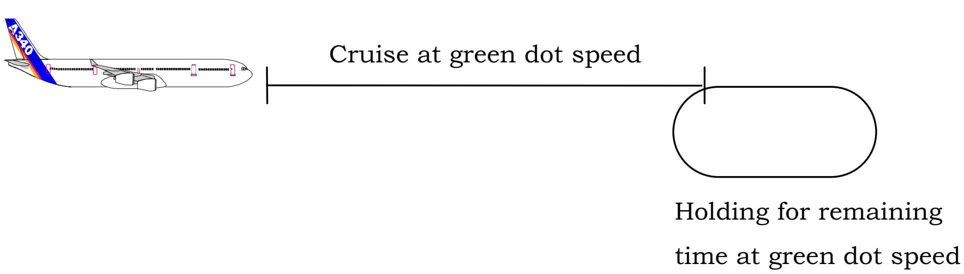
If A.T.C. informs 15 minutes before reaching a fix and that 10 minutes holding is expected. Two options are possible:

- The aircraft is flown 15 minutes at cruise speed and holds for 10 minutes at green dot speed.
- The aircraft performs the cruise to reach the fix at green dot speed and holds for the remaining time at the same speed.

Holding at cruise



Holding optimization



ATC restrictions may not permit a cruise speed reduction at the cruise flight level, or permit a hold at the cruise flight level. The standard procedure would be to continue to the top of descent at cruise speed and descend to a flight level to join the stack. However if ATC permit a linear hold it can give significant fuel savings.

However the amount of savings is very dependant on the characteristics of the aircraft type. The increase in time in the cruise depends on how much slower green dot speed is compared to the normal cruise speed. This increase was much higher with the A320 than the A340. In addition, most aircraft, flying the same cruise distance at green dot speed actually uses a little more fuel at these altitudes. The following table shows the gains due to cruising slower and spending less time in the hold at the cruise flight level.

Advantages of a 15min linear hold at cruise altitude at Green Dot speed

Aircraft type	Weight kg	Cruise Flight Level	Cruise Speed	Fuel savings kg
A300	120000	350	0.8	95
A310	110000	350	0.8	115
A318	50000	350	0.78	120
A319	50000	350	0.78	135
A320	60000	350	0.78	80
A321	70000	350	0.78	50
A330	180000	390	0.82	95
A340-200	200000	390	0.82	10
A340-300	200000	390	0.82	45
A340-500/600	270000	390	0.82	5

The high green dot speed for the A340 leads to very little advantage in linear holding. However the other aircraft show significant benefits.

If the increase in cruise time can be used to reducing the time in the holding pattern or stack, then the benefits will be similar to those shown in the table above. However the constraints of ATC are unlikely to let these benefits accrue.

5.6 APPROACH

5.6.1 FLIGHT PATH PRIOR TO GLIDE SLOPE INTERCEPTION

Procedures used in the approach phase can affect the amount of fuel consumed in this phase of the flight. The glide slope can be intercepted either horizontally between 1500ft and 2000ft or in a descending flight path above 2000ft. This latter method uses less fuel, but the amount is difficult to quantify, as it depends on the exact flight paths in each case. However, the most important feature of an approach is that it should be well executed, stabilized and safe. None of these features should be compromised in an attempt to save fuel, and the procedure flown should be that appropriate to the airport, runway, equipment, conditions, etc.

5.6.2 LANDING GEAR EXTENSION

The standard procedure is that Gear Down is selected down when Conf 2 (or flap 20 for A300/310) is achieved. The effect of extending the gear prior to this point will increase fuel burn, but the amount is difficult to quantify without knowing when the gear is extended. However, the most important feature of an approach is that it should be well executed, stabilized and safe. The use of gear is often one of the means of achieving this through speed control, and gear extension should not be delayed to save fuel.

6. DETAILED SUMMARY

6.1 INTRODUCTION

In this brochure it can be seen that there are many ways of influencing the fuel burn of an aircraft, but most depend on the way that the sector is planned and flown. Maximising the fuel economy requires:

- Good flight planning based on good data.
- Correct aircraft loading (weight and cg).
- An aerodynamically clean aircraft.
- Optimal use of systems (APU, Bleed, Flaps/Slats, Gear, etc).
- Flight Procedures using speeds and altitudes appropriate to the companies economic priorities.
- Use of the FMGS in the managed mode.
- Use of performance factors in flight planning and in the FMGS derived from an ongoing aircraft performance monitoring program.

6.2 GENERAL GUIDELINES

6.2.1 PRE-FLIGHT PROCEDURES

- For most Airbus aircraft, an aft CG position saves fuel.
- Excess weight costs fuel. Minimize zero fuel weight and embarked fuel.
- A good flight planning system will minimise fuel through correct optimisation.
- An aircraft performance measurement system and good flight planning will give confidence in fuel burn reducing extra reserve.
- Keep A.P.U. running during short turnarounds to reduce A.P.U. start cycles.
- Use ground power, when possible to save both fuel and A.P.U. life.

- Do not start engines until ready to go.
- If considered operationally acceptable, taxi with one engine out.
- Keep the aircraft in an aerodynamically clean condition.

6.2.2 TAKE-FF AND INITIAL CLIMB

- Bleeds off fuel improvements normally negated by APU fuel burn
- Lower configurations do save fuel.
- Flex thrust cost fuel but saves engine costs.
- Noise flight paths cost fuel

6.2.3 CLIMB

- Climb as close as possible to the optimum climb law.
- Fast Climb speeds use more fuel (except A340)

6.2.4 CRUISE

- The best speed for fuel burn (very low cost index) is slow and has a big time penalty.
- If possible, fly in managed mode at the cost index appropriate to the airlines economic priorities.
- Flying faster than the FMGS economical Mach number costs fuel.
- Try to fly at optimum altitude. Chase the optimum altitude.
- Flying at the cross-over altitude is faster, but costs fuel.
- Step Climb around the optimum altitude (see FCOM).
- Avoid delays in initiating a step climb.
- For short stage lengths, fly at an appropriate altitude (see FCOM).
- Wind variations with altitude can give advantages in flying at lower altitudes.

6.2.5 DESCENT

- Diminishing descent speed can allow significant fuel savings.
- Avoid early descents

6.2.6 HOLDING

- The best combination for fuel burn is clean configuration at green dot speed.
- Manoeuvrability, speed or ATC restrictions may require a hold in configuration 1 at S speed.
- If holding is to be anticipated, linear holding saves fuel.

6.2.7 APPROACH

- Avoid extending gear unnecessarily early.

6.3 FUEL SAVINGS

The following table gives examples of the savings possible through the application of correct procedures and practices. The values represent typical saving as there is variation dependant on the actual base case considered. However these figures serve to illustrate the magnitude of savings being achieved (or penalties being paid). The savings are expressed in kg of fuel for one flight, with the sector length being representative for each aircraft.

Fuel Savings Possible in the Pre-Flight phase

Item	Variation	A300	A310	A320	A330	A340-200/300	A340-500/600
Sector		2000nm	2000nm	1000nm	4000nm	6000nm	6000nm
CG	mid to aft	710	330	0	600	900	1550
Weight	-1% MTOW	380	250	100	800	1530	1920
EO Taxi	8 minutes	50	40	25	50	50	70
APU	3 min Grd Power	9	9	6	10	10	14
Ground Idle	3 min APU	18	18	9	15-24	3	9
Misrigged Slat	15mm to zero	90	90	60	270	270	270
Peeling Paint	1sq m slat to zero	12	12	8	60	60	60

Fuel Savings in the In Flight Phase

Item	Variation	A300	A310	A320	A330	A340-200/300	A340-500/600
Sector		2000nm	2000nm	1000nm	4000nm	6000nm	6000nm
TO Conf	Max to min F/S	15	15	10	24	-	50
Climb Rating	Derate 2 to full Climb	NA	NA	NA	30	120-320	445
Climb Speed	330 to 300kias	10	15	70	35	25	-10
Cruise Altitude	Optimum to −2000′	65	80	80	100	95	135
Cruise Altitude	Optimum to +2000′	90	60	25	145	30	25
Cruise Mach	Mecon+.01 to Mecon	230	430	40	330	900	2540
Delayed Climb	CFP to 500nm late	240	220	180	330	390	340
CG	mid to aft	710	330	0	600	900	1550
Descent Speed	Max to 300kt	35	40	30	70	75	100
Early Descent	CFP to 2min early	70	70	50	80	95	135
Hold	Green Dot Clean Conf	190	135	30	205	230	130

6.4 ECONOMIC BENEFITS

It may be that 5 or 10 kg extra fuel per flight does not seem significant in terms of the total fuel burn during the flight. However this saving accumulates with every flight. Sometimes the savings for an A340 seem worthwhile compared with the equivalent value for an A320, but the increased number of flight cycles for an A320 can make this saving more significant than that of the A340. The only way to assess the impact of any saving is to look at it over a given time span.

The economic impact calculations have assumed typical yearly utilisation rates, average sector lengths and sectors per year as follows:

Utilisation	A300	A310	A320	A330	A340
Flying Hours/year	2600	3200	2700	2900	4700
Average sector - nm	2000	2000	1000	4000	6000
Average flight time - hr	4.5	4.6	2.4	8.5	13.8
No of sectors/year	580	700	1125	340	340

The following table shows the annual cost savings for one aircraft associated with various fuel savings for each Airbus type based on the above utilisation figures. Fuel is assumed to cost $1/us gallon (33cents/kg).

Savings/flight	A300	A310	A320	A330	A340
10kg	$1920	$2310	$3720	$1120	$1120
50kg	$9600	$11550	$18600	$5600	$5600
250kg	$48000	$57750	$93000	$28000	$28000
1000kg	$192000	$231000	$372000	$112000	$112000

7. CONCLUSIONS

There are many factors that influence the fuel used by aircraft, and these are highlighted in this report. The unpredictability of fuel prices, together with the fact that they represent such a large burden to the airline has prompted Airbus to be innovative in the field of fuel conservation. The relationship between fuel used and flight time is such that sometimes compromise is necessary to get the best economics. Whether in the field of design engineering or in flight operations support, we have always maintained a competitive edge. Whether it is in short or ample supply, we have always considered fuel conservation a subject worth revisiting.

Fuel conservation affects many areas including flight planning, flight operations and maintenance. Airbus is willing and able to support airlines with operational support in all the appropriate disciplines. Despite the increasing efficiency of modern aircraft it is a subject that demands continuous attention and an airline that can focus on the subject, together with the Operation Support of Airbus is best placed to meet the challenges of surviving and profiting in the harsh airline environment of the 21st century.

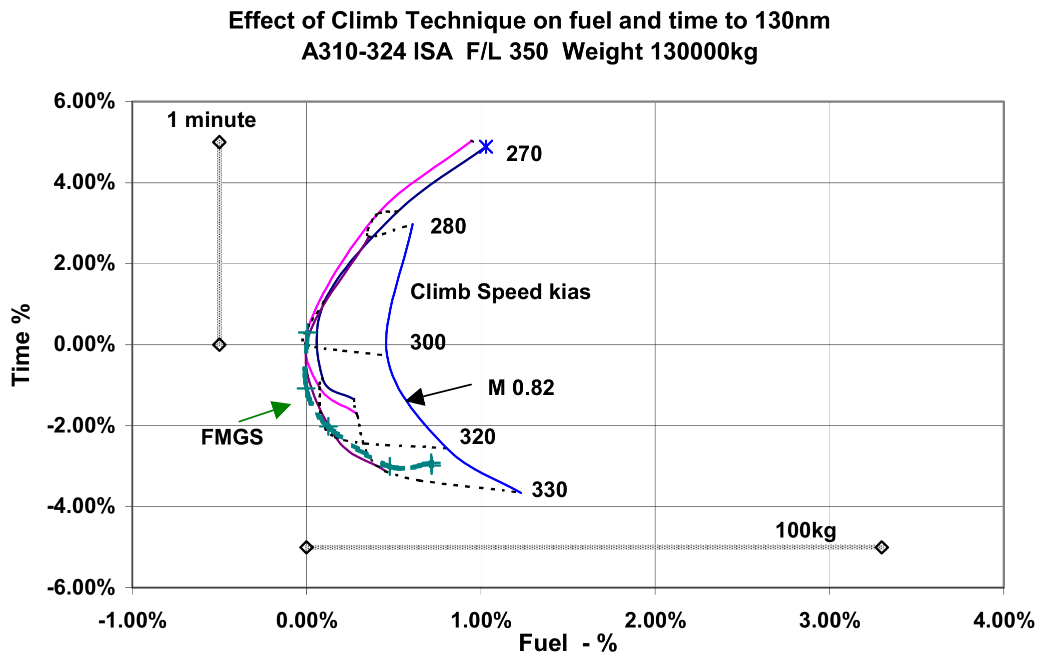
8. APPENDICES

These appendices contain climb and descent graphs for some of the other variants of Airbus aircraft. Each airframe/engine combination have different characteristics. Even the weight variant can influence these characteristics. It is therefore impossible to include all variants, but the selection shown will give an idea of the sensitivities of fuel burn and time to technique.

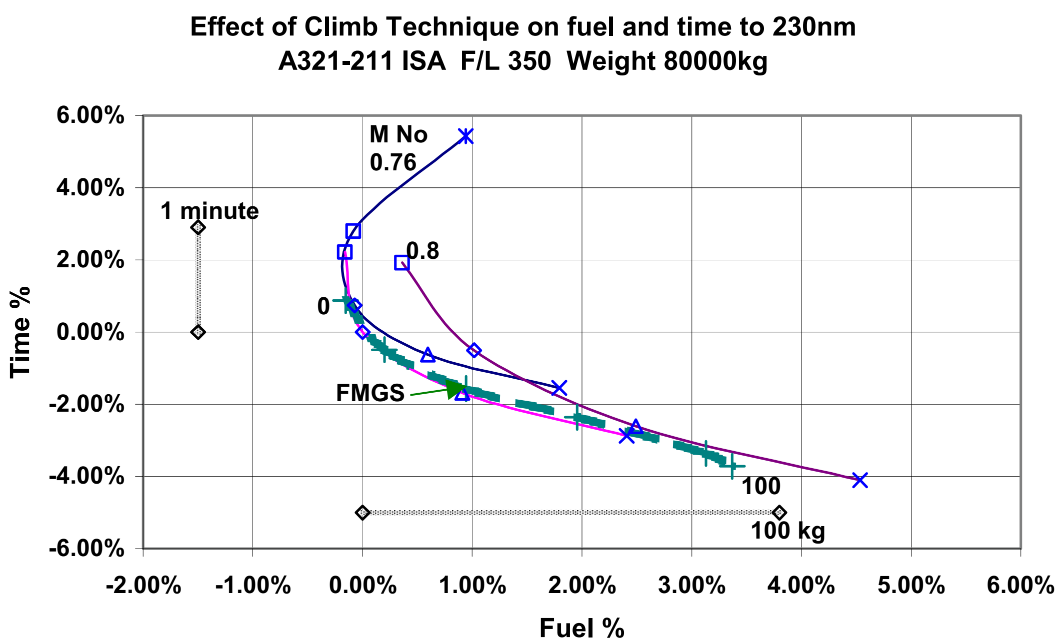
APPENDIX A (CLIMB CHARTS)

The climb chart for the A300 is given in the main report (5.2.3)

The **A310** shows similar characteristics and is shown below. Note that the lower mach numbers (0.76, 0.78 and 0.8) show no variation.

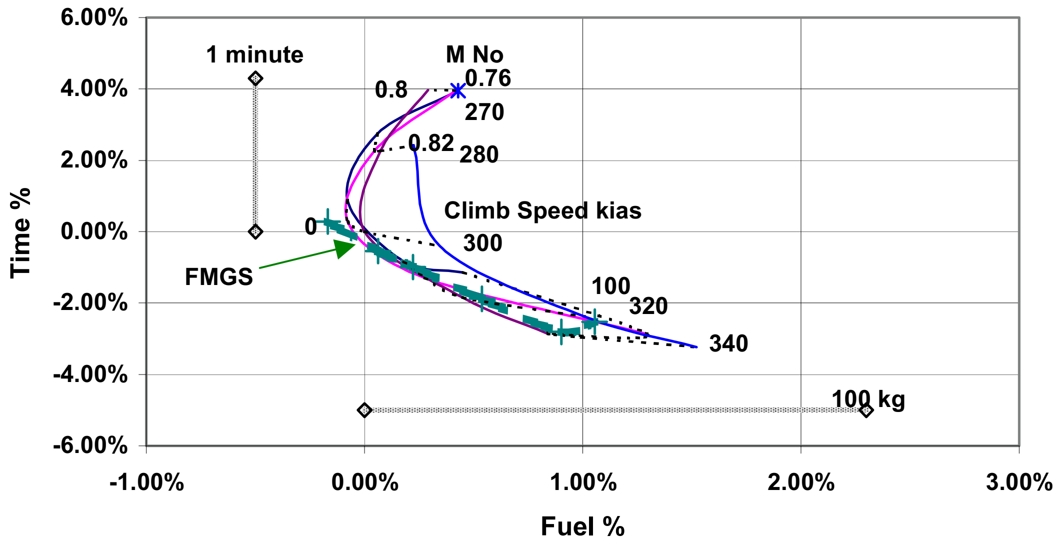


The main report gives the climb chart for the A320 which is similar to the A318 and A319. The **A321** however shows more significant differences.



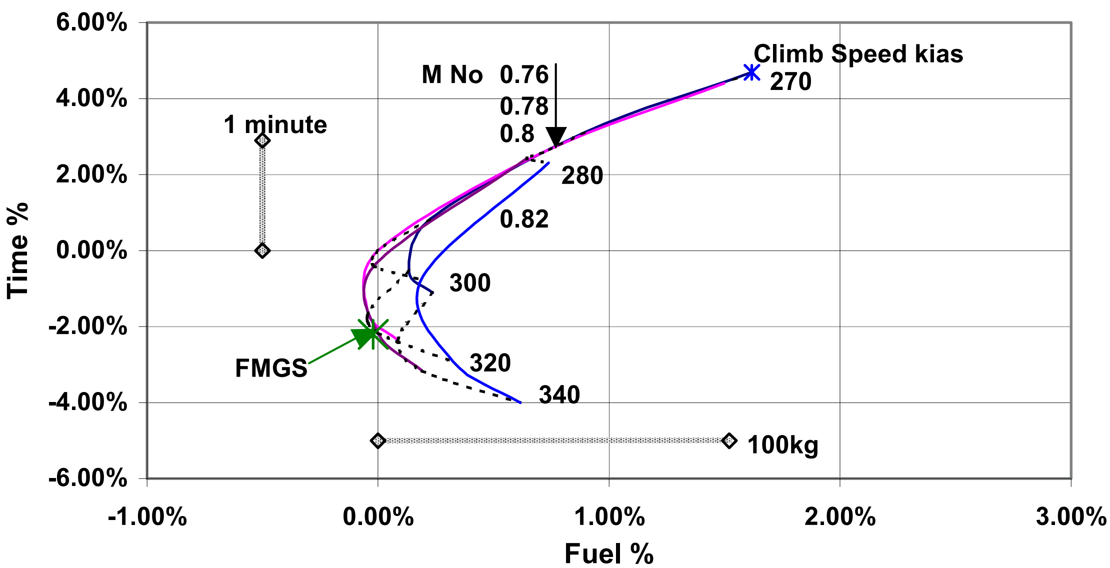
The **A330** aircraft show characteristics similar to the A321 and an example is shown below.

Effect of Climb Technique on fuel and time to 150nm
A330-343 ISA F/L 350 Weight 190000kg



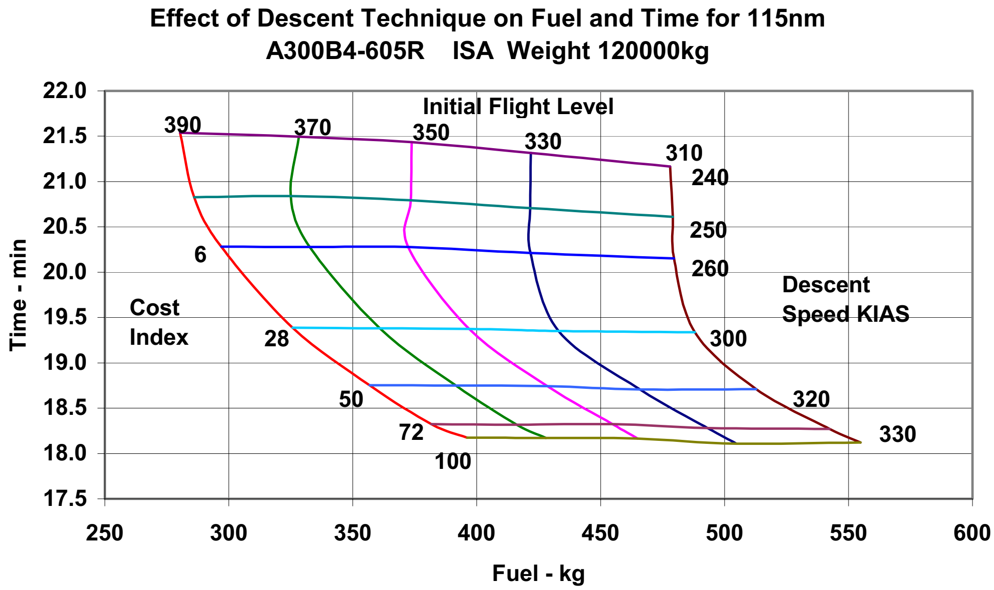
The **A340-200/300** series show characteristics approaching that of the A340-500/600 but still shows minimum fuel at a speed lower than max, unlike the A340-500/600 (see 5.2.3).

Effect of Climb Technique on fuel and time to 220nm
A340-313E ISA F/L 350 Weight 240000kg

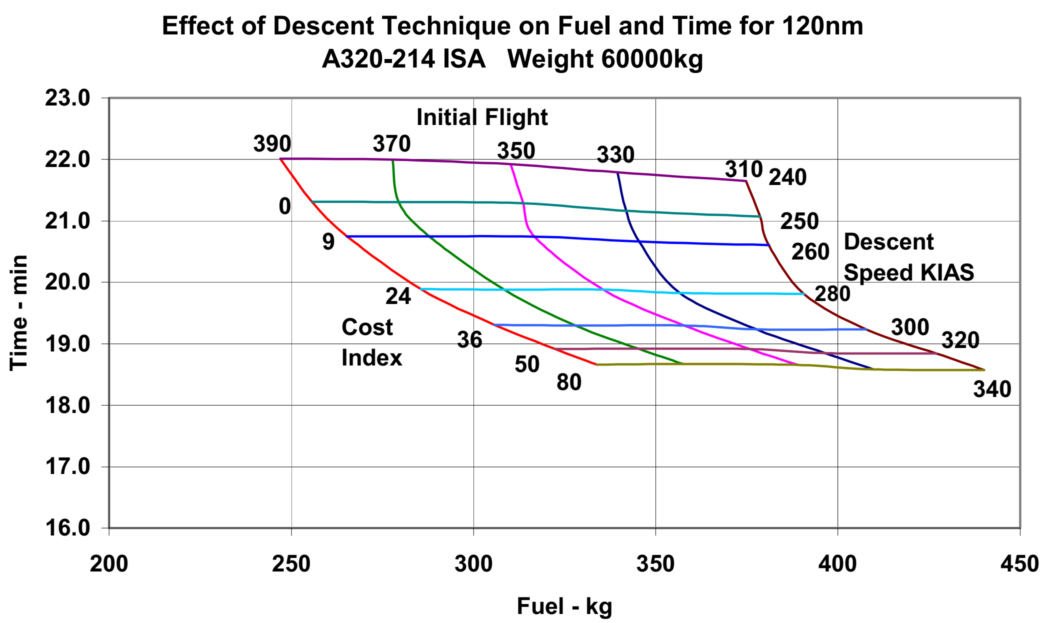


APPENDIX B (DESCENT CHARTS)

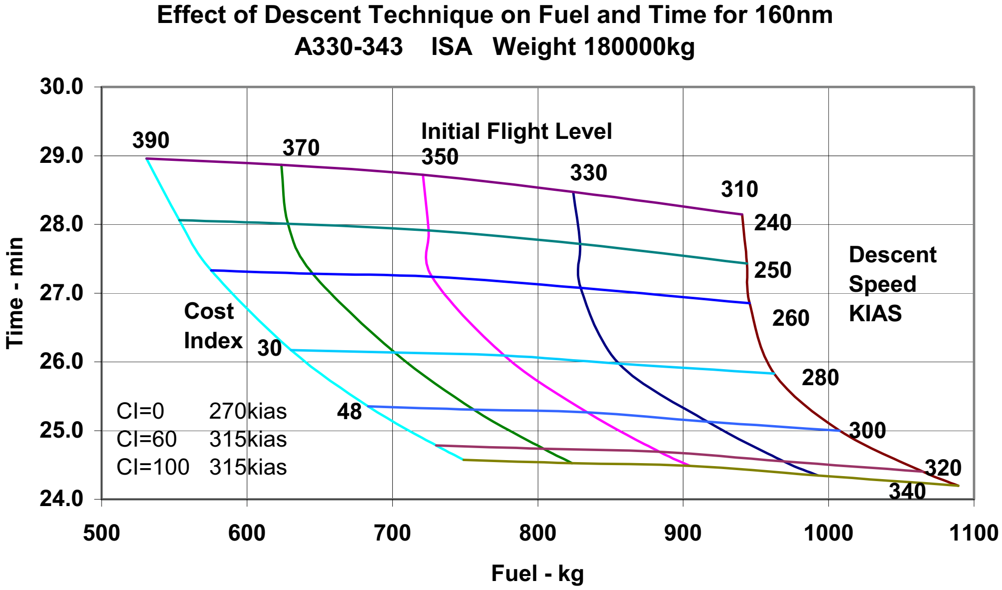
The **A300** shows similar characteristics to the A310 in the main report.



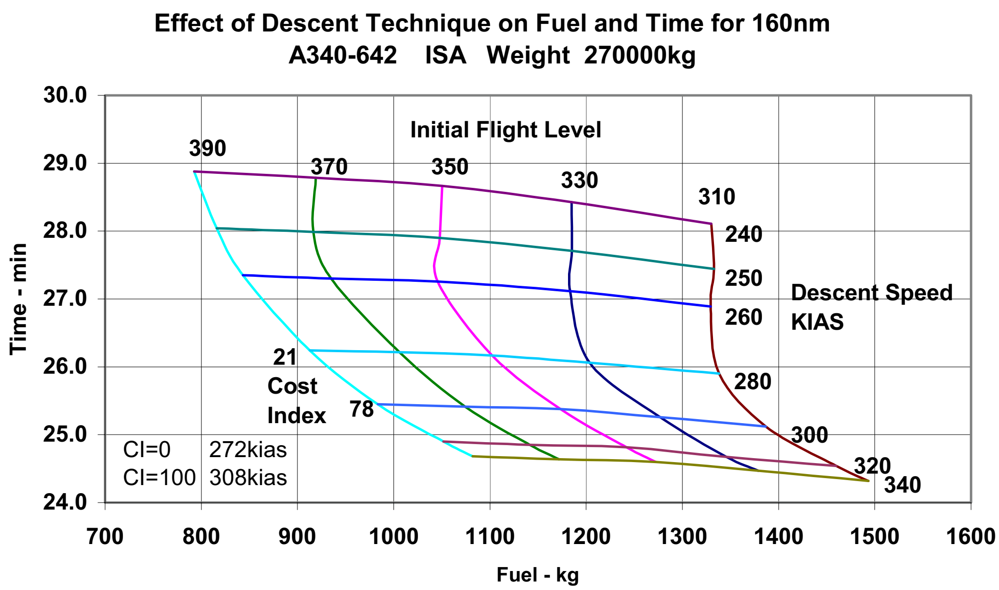
The **A320** shown below has similar characteristics to the A318, A319 and A321.



The following shows an example of an **A330**:



Most of the **A340**'s have similar speed characteristics to the A340-642 shown below. The A340-200 does however show an improvement in fuel for speeds lower than 260kts.



Fuel Conservation
Airframe Maintenance for Environmental Performance

Dave Anderson
Flight Operations Engineering
Boeing Commercial Airplanes
September 2006

Maintenance Personnel

Opportunities For Fuel Conservation

- Empty weight control
- Airframe maintenance
- Systems maintenance

Reducing Aircraft Weight Reduces Fuel Burned

Approximate %Block Fuel Savings Per
453 kg (1000 lb) ZFW Reduction

717-200	737-3/4/500	737-6/7/8/900	757-200/300	767-2/3/400	777-200/300	747-400
.9%	.7%	.6%	.5%	.3%	.2%	.2%

Reducing OEW Reduces ZFW

Items To Consider

- Passenger service items
- Passenger entertainment items
- Empty Cargo and baggage containers
- Unneeded Emergency equipment
- Excess Potable water

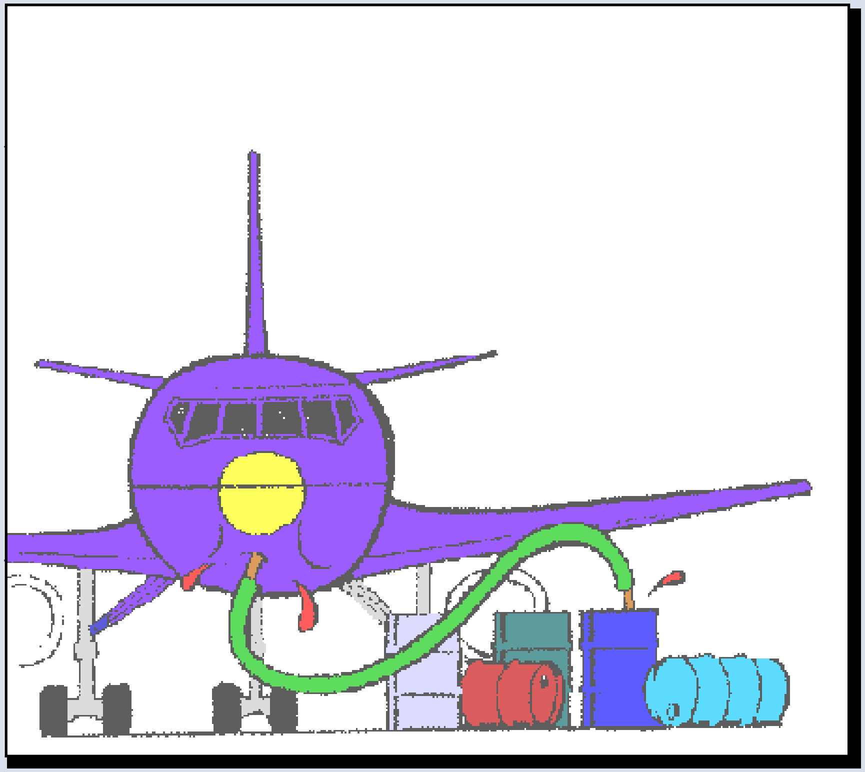
Reducing OEW Reduces ZFW

- Operating empty weight (OEW) increases on average 0.1% to 0.2% per year, leveling off around 1% after 5 to 10 years
- Most OEW growth is mainly due to moisture and dirt

Reducing Aircraft Drag Reduces Fuel Burned

Effect of a 1% Drag Increase In Terms Of Gallons Per Year

- 747 ≈ 100,000
- 777 ≈ 70,000
- 767 ≈ 30,000
- 757 ≈ 25,000
- 737 ≈ 15,000
- 727 ≈ 30,000



(Assumes typical aircraft utilization rates)

Total Drag Is Composed Of:

Compressible drag ≈ drag due to high Mach

- Shock waves, separated flow

Induced (vortex) drag ≈ drag due to lift

- Downwash behind wing, trim drag

Parasite drag ≈ drag **not** due to lift

- Shape of the body, skin friction, leakage, interference between components
- Parasite drag **includes** **excrescence** drag

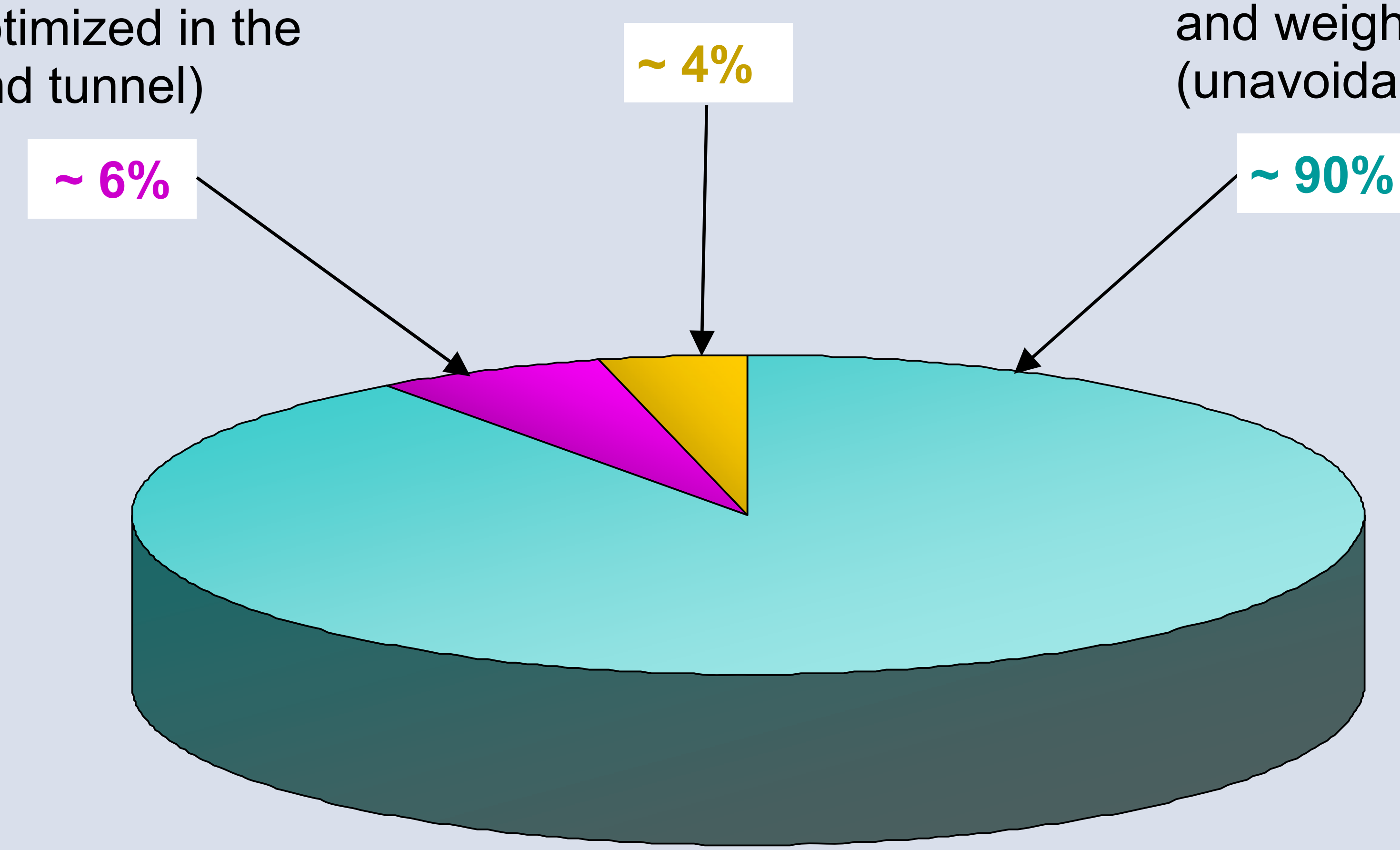
Contributors To Total Airplane Drag

(For a new airplane at cruise conditions)

Pressure, trim and interference drag (optimized in the wind tunnel)

Excrescence drag (this can increase)

Drag due to airplane size and weight (unavoidable)



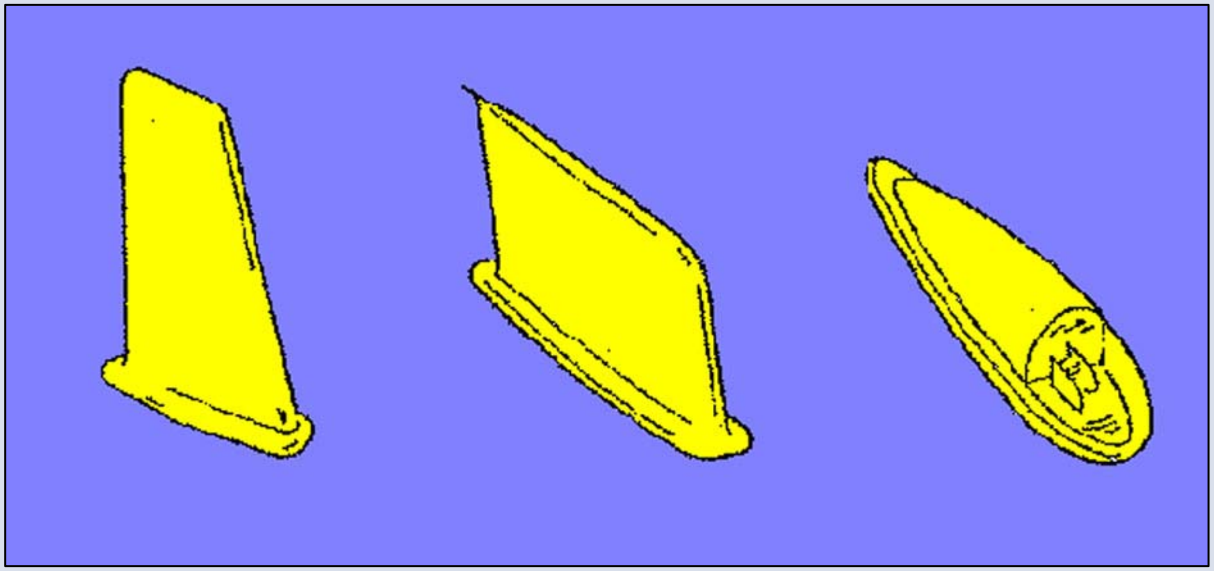
What Is Excrescence Drag?

The additional drag on the airplane due to the sum of all deviations from a smooth sealed external surface

Proper maintenance can prevent an increase in excrescence drag

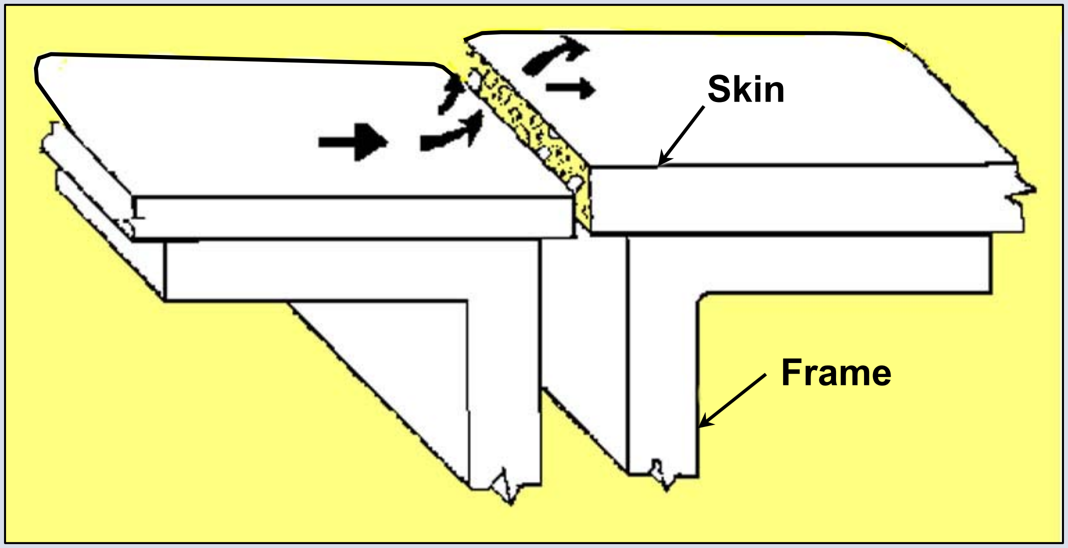
Discrete Items

- Antennas, masts, lights
- Drag is a function of design, size, position

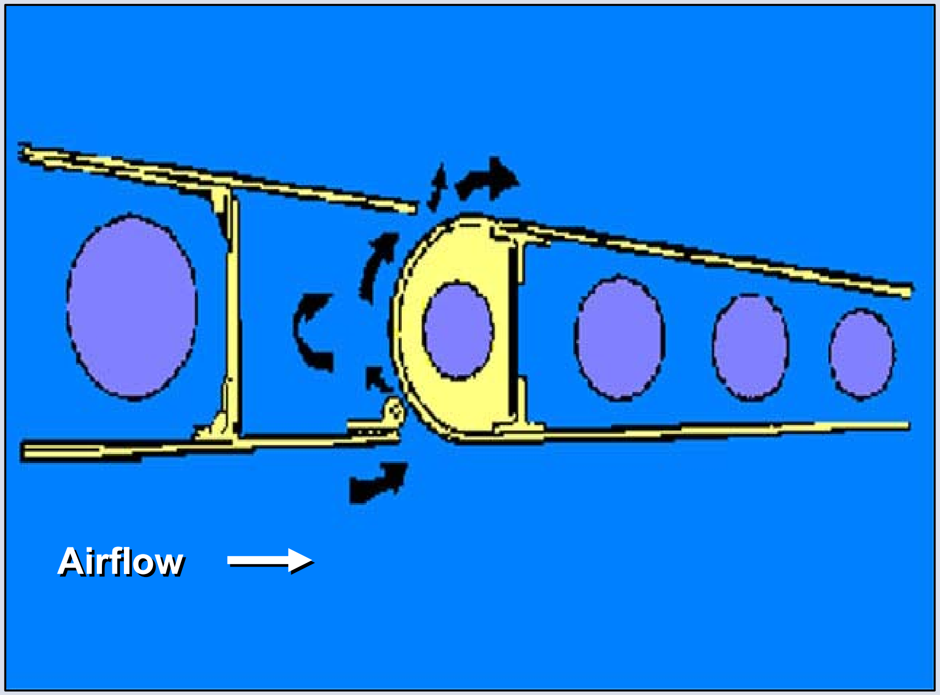


Mismatched Surfaces and Gaps

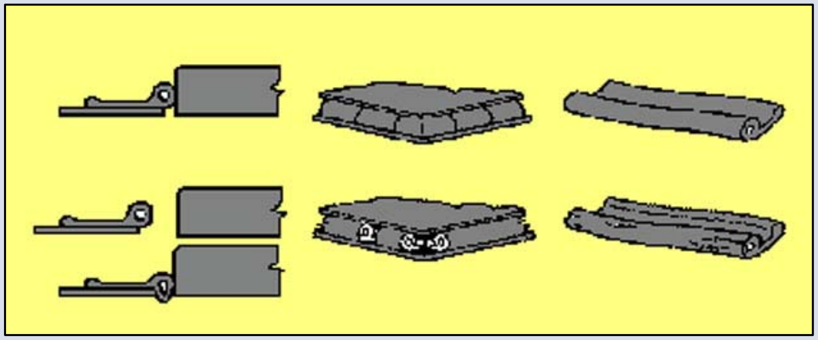
Steps at skin joints, around windows, doors, control surfaces, and access panels



Internal Airflow

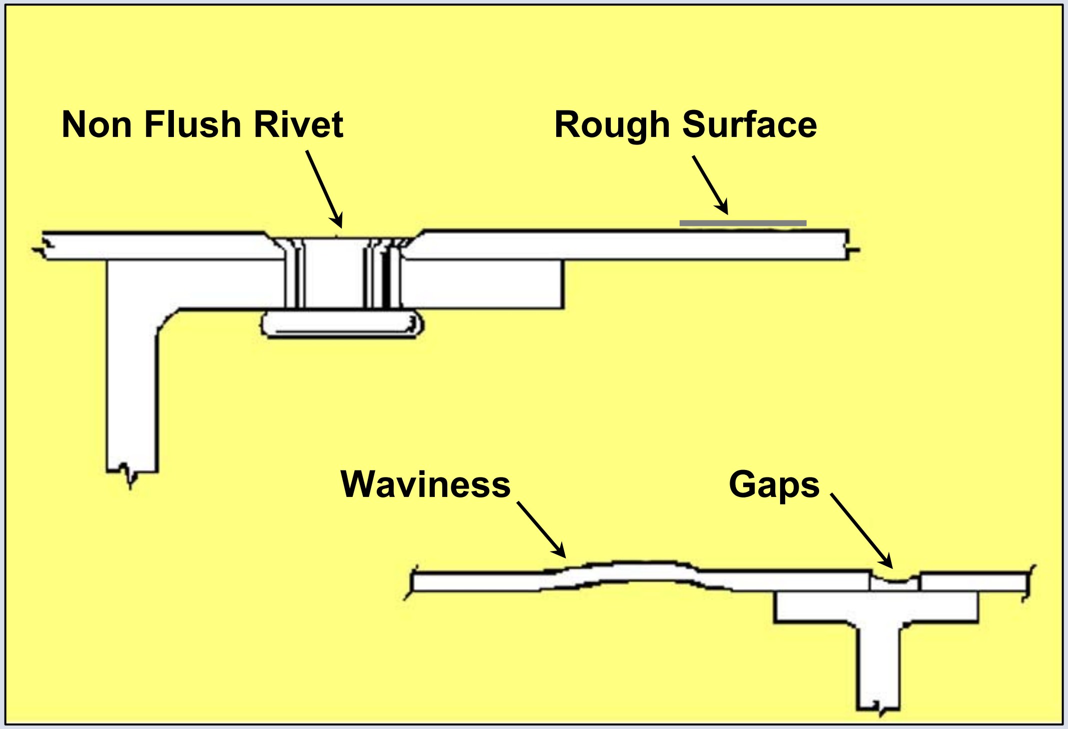


Leaks through gaps, holes, and aerodynamic seals



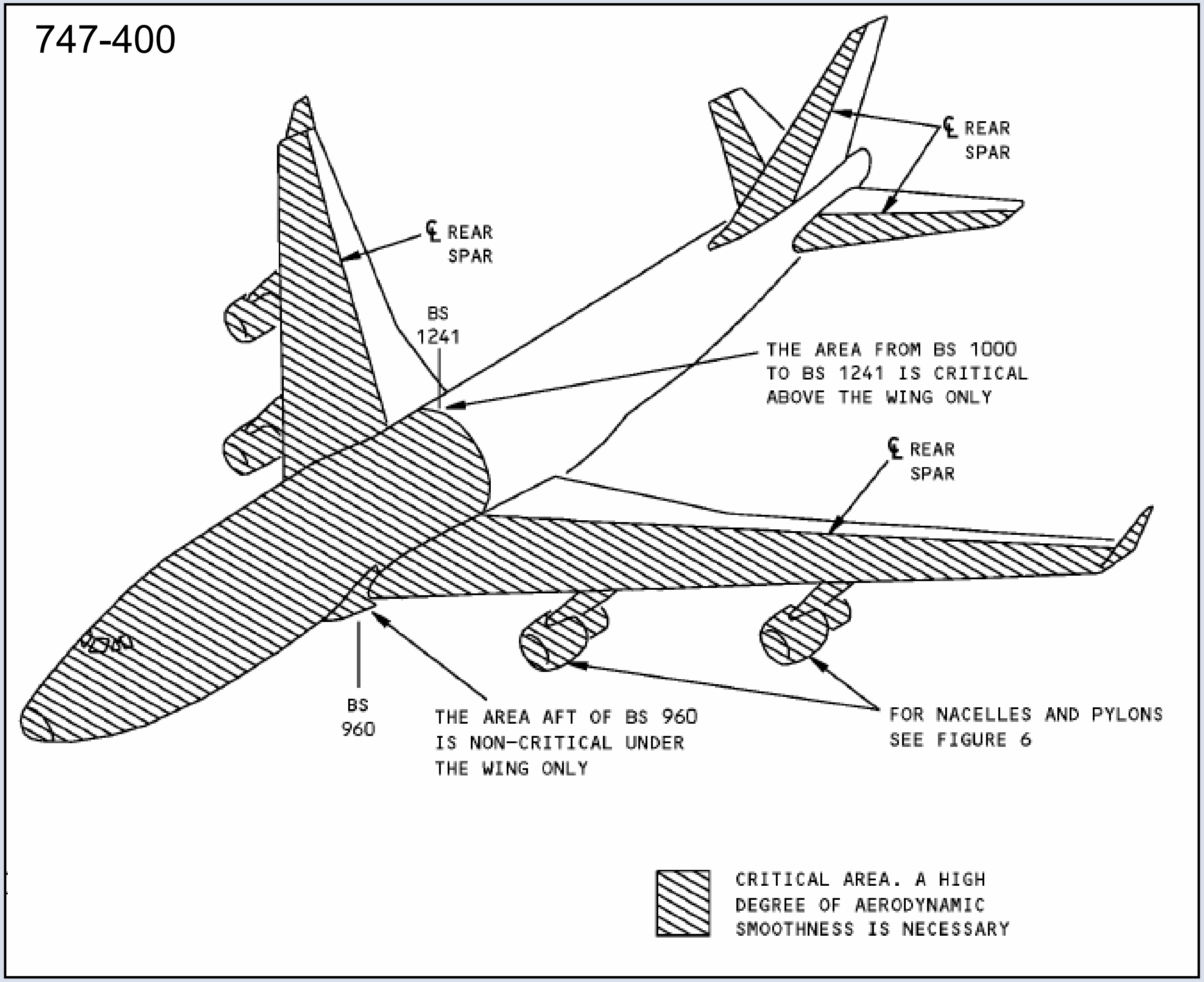
Roughness
(Particularly Bad Near Static Sources)

- Non-flush fasteners, rough surface
- Waviness, gaps



Most Important in Critical Areas

- Structural Repair Manuals Identifies Critical Areas



Average Results Of In-service Drag Inspections

Average total airframe drag deterioration ~ 0.65%, composed mainly of:

- Control Surface Rigging ≈ 0.25%
- Deteriorated Seals ≈ 0.20%
- Misfairs ≈ 0.1%
- Roughness ≈ 0.05%
- Other ≈ 0.05%

A well-maintained airplane should not exceed 0.5% drag increase from its new airplane level

Regular Maintenance Minimizes Airframe Deterioration

- Flight control rigging
- Misalignments, mismatches and gaps
- Aerodynamic seals
- Empty weight control
- Exterior surface finish
- Instrument calibration/maintenance

Maintain a Clean Airplane

- Maintain surface finish
- Fluid leaks contribute to drag
- Periodic washing of exterior is beneficial
  - 0.1% drag reduction if excessively dirty
  - Minimizes metal corrosion and paint damage
  - Location of leaks and local damage
- Customer aesthetics

Instrument Calibration/Maintenance

- Speed measuring equipment has a large impact on fuel mileage - keep airspeed system maintained
- If speed is not accurate then aircraft is flying faster or slower than intended - airspeed reads 1% low, aircraft flying 1% fast
- On the 747-400, flying 0.01M faster then intended can increase fuel burn by over 1%

Proper and Continuous Airframe and Engine Maintenance Will Keep Aircraft Performing at Their Best!

Conclusions

It Takes the Whole Team to Win

- Large fuel (and emissions) savings results from the accumulation many smaller fuel-saving actions and policies
- Dispatch, flight operations, flight crews, **maintenance**, management, all need to contribute

Thank You!

FLIGHT
OPERATIONS
ENGINEERING

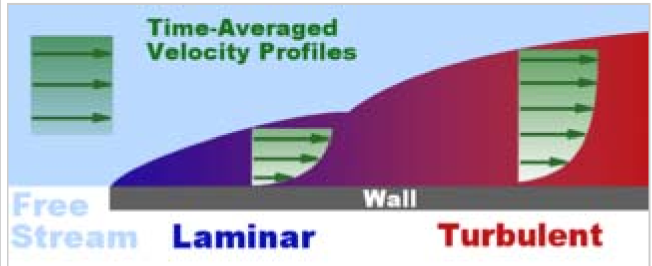
End of Fuel Conservation

Airframe Maintenance for Environmental Performance

Dave Anderson
Flight Operations Engineering
Boeing Commercial Airplanes
September 2006

Boundary layer

From Wikipedia, the free encyclopedia



Boundary Layer visualization, showing transition from laminar to turbulent condition

In physics and fluid mechanics, a **boundary layer** is that layer of fluid in the immediate vicinity of a bounding surface. In the Earth's atmosphere, the planetary boundary layer is the air layer near the ground affected by diurnal heat, moisture or momentum transfer to or from the surface. On an aircraft wing the boundary layer is the part of the flow close to the wing. The *boundary layer effect* occurs at the field region in which all changes occur in the flow pattern. The boundary layer distorts surrounding nonviscous flow. It is a phenomenon of viscous forces. This effect is related to the Reynolds number.

Laminar boundary layers come in various forms and can be loosely classified according to their structure and the circumstances under which they are created. The thin shear layer which develops on an oscillating body is an example of a Stokes layer, whilst the Blasius boundary layer refers to the well-known similarity solution for the steady boundary layer attached to a flat plate held in an oncoming unidirectional flow. When a fluid rotates, viscous forces may be balanced by Coriolis effects, rather than convective inertia, leading to the formation of an Ekman layer. Thermal boundary layers also exist in heat transfer. Multiple types of boundary layers can coexist near a surface simultaneously.

Contents

Aerodynamics

The aerodynamic boundary layer was first defined by Ludwig Prandtl in a paper presented on August 12, 1904 at the third International Congress of Mathematicians in Heidelberg, Germany. It allows aerodynamicists to simplify the equations of fluid flow by dividing the flow field into two areas: one inside the boundary layer, where viscosity is dominant and the majority of the drag experienced by a body immersed in a fluid is created, and one outside the boundary layer where viscosity can be neglected without significant effects on the solution. This allows a closed-form solution for the flow in both areas, which is a significant simplification over the solution of the full Navier-Stokes equations. The majority of the heat transfer to and from a body also takes place within the boundary layer, again allowing the equations to be simplified in the flow field outside the boundary layer.

The thickness of the velocity boundary layer is normally defined as the distance from the solid body at which the flow velocity is 99% of the freestream velocity, that is, the velocity that is calculated at the surface of the body in an inviscid flow solution. The no-slip condition requires the flow velocity at the surface of a solid object be zero and the fluid temperature be equal to the temperature of the surface. The flow velocity will then increase rapidly within the boundary layer, governed by the boundary layer equations, below. The thermal boundary layer thickness is similarly the distance from the body at which the temperature is 99% of the temperature found from an inviscid solution. The ratio of the two thicknesses is governed by the Prandtl number. If the Prandtl number is 1, the two boundary layers are the same thickness. If the Prandtl number is greater than 1, the thermal boundary layer is thinner than the velocity boundary layer. If the Prandtl number is less than 1, which is the case for air at standard conditions, the thermal boundary layer is thicker than the velocity boundary layer.

In high-performance designs, such as sailplanes and commercial transport aircraft, much attention is paid to controlling the behavior of the boundary layer to minimize drag. Two effects must to be considered. First, the boundary layer adds to the effective thickness of the body, through the displacement thickness, hence increasing the pressure drag. Secondly, the shear forces at the surface of the wing create skin friction drag.

At high Reynolds numbers, typical of full-sized aircraft, it is desirable to have a laminar boundary layer. This results in a lower skin friction due to the characteristic velocity profile of laminar flow. However, the boundary layer inevitably thickens and becomes less stable as the flow develops along the body, and eventually becomes turbulent, the process known as boundary layer transition. One way of dealing with this problem is to suck the boundary layer away through a porous surface (see Boundary layer suction). This can result in a reduction in drag, but is usually impractical due to the mechanical complexity involved and the power required to move the air and dispose of it.

At lower Reynolds numbers, such as those seen with model aircraft, it is relatively easy to maintain laminar flow. This gives low skin friction, which is desirable. However, the same velocity profile which gives the laminar boundary layer its low skin friction also causes it to be badly affected by adverse pressure gradients. As the pressure begins to recover over the rear part of the wing chord, a laminar boundary layer will tend to separate from the surface. Such flow separation causes a large increase in the pressure drag, since it greatly increases the effective size of the wing section. In these cases, it can be advantageous to deliberately trip the boundary layer into turbulence at a point prior to the location of laminar separation, using a turbulator. The fuller velocity profile of the turbulent boundary layer allows it to sustain the adverse pressure gradient without separating. Thus, although the skin friction is increased, overall drag is decreased. This is the principle behind the dimpling on golf balls, as well as vortex generators on light aircraft. Special wing sections have also been designed which tailor the pressure recovery so laminar separation is reduced or even eliminated. This represents an optimum compromise between the pressure drag from flow separation and skin friction from induced turbulence.

Naval Architecture

Many of the principles that apply to aircraft also apply to ships and offshore platforms. There are a few key differences.

One is the mass of the boundary layer. Since a good portion of the boundary layer travels at or near the speed of the ship, the energy required to accelerate and decelerate this additional mass must be taken into account. When calculating the power required by the engine, this mass is added to the mass of the ship. In aircraft, this additional mass is not usually taken into account because the weight of the air is so small. However, in ship design, this mass can easily reach 1/4 or 1/3 of the weight of the ship and therefore represents a significant drag in addition to frictional drag.

Boundary layer equations

The deduction of the **boundary layer equations** was perhaps one of the most important advances in fluid dynamics. Using an order of magnitude analysis, the well-known governing Navier-Stokes equations of viscous fluid flow can be greatly simplified within the boundary layer. Notably, the characteristic of the partial differential equations (PDE) becomes parabolic, rather than the elliptical form of the full Navier-Stokes equations. This greatly simplifies the solution of the equations. By making the boundary layer approximation, the flow is divided into an inviscid portion (which is easy to solve by a number of methods) and the boundary layer, which is governed by an easier to solve PDE. The Navier-Stokes equations for a two-dimensional steady incompressible flow in cartesian coordinates are given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2})$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2})$$

where u and v are the velocity components, ρ is the density, p is the pressure, and ν is the kinematic viscosity of the fluid at a point.

The approximation states that, for a sufficiently high Reynolds number the flow over a surface can be divided into an outer region of inviscid flow unaffected by viscosity (the majority of the flow), and a region close to the surface where viscosity is important (the boundary layer). Let *u* and *v* be streamwise and transverse (wall normal) velocities respectively inside the boundary layer. Using asymptotic analysis, it can be shown that the above equations of motion reduce within the boundary layer to become

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial y^2}$$

and the remarkable result that

$$\frac{1}{\rho}\frac{\partial p}{\partial y} = 0$$

The asymptotic analysis also shows that v, the wall normal velocity, is small compared with u the streamwise velocity, and that variations in properties in the streamwise direction are generally much lower than those in the wall normal direction.

Since the static pressure p is independent of y, then pressure at the edge of the boundary layer is the pressure throughout the boundary layer at a given streamwise position. The external pressure may be obtained through an application of Bernoulli's Equation. Let u_0 be the fluid velocity outside the boundary layer, where u and u_0 are both parallel. This gives upon substituting for p the following result

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = u_0\frac{\partial u_0}{\partial x} + \nu\frac{\partial^2 u}{\partial y^2}$$

with the boundary condition

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

For a flow in which the static pressure p also does not change in the direction of the flow then

$$\frac{\partial p}{\partial x} = 0$$

so u_0 remains constant.

Therefore, the equation of motion simplifies to become

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2}$$

These approximations are used in a variety of practical flow problems of scientific and engineering interest. The above analysis is for any instantaneous laminar or turbulent boundary layer, but is used mainly in laminar flow studies since the mean flow is also the instantaneous flow because there are no velocity fluctuations present.

Turbulent boundary layers

The treatment of turbulent boundary layers is far more difficult due to the time-dependent variation of the flow properties. One of the most widely used techniques in which turbulent flows are tackled is to apply Reynolds decomposition. Here the instantaneous flow properties are decomposed into a mean and fluctuating component. Applying this technique to the boundary layer equations gives the full turbulent boundary layer equations not often given in literature:

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} = 0$$

Using the same order-of-magnitude analysis as for the instantaneous equations, these turbulent boundary layer equations generally reduce to become in their classical form:

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} = 0$$

$$\overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial y} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x} + \nu\frac{\partial^2 \overline{u}}{\partial y^2} - \frac{\partial}{\partial y}(\overline{u'v'})$$

$$\frac{\partial \overline{p}}{\partial y} = 0$$

The additional term $\overline{u'v'}$ in the turbulent boundary layer equations is known as the Reynolds shear stress and is unknown a priori. The solution of the turbulent boundary layer equations therefore necessitates the use of a turbulence model, which aims to express the Reynolds shear stress in terms of known flow variables or derivatives. The lack of accuracy and generality of such models is the single major obstacle which inhibits the successful prediction of turbulent flow properties in modern fluid dynamics.

Boundary layer turbine

This effect was exploited in the Tesla turbine, patented by Nikola Tesla in 1913. It is referred to as a bladeless turbine because it uses the boundary layer effect and not a fluid impinging upon the blades as in a conventional turbine. Boundary layer turbines are also known as cohesion-type turbine, bladeless turbine, and Prandtl layer turbine (after Ludwig Prandtl).

See also

- Boundary layer suction
- Coandă effect
- Planetary boundary layer
- Shear stress

External links

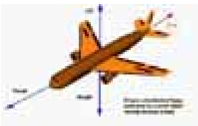
- National Science Digital Library - Boundary Layer
- Moore, Franklin K., "*Displacement effect of a three-dimensional boundary layer*". NACA Report 1124, 1953.

- Benson, Tom, "*Boundary layer*". NASA Glenn Learning Technologies.
- Boundary layer separation
- *Boundary layer equations: Exact Solutions* - from EqWorld

References

- A.D. Polyanin and V.F. Zaitsev, *Handbook of Nonlinear Partial Differential Equations*, Chapman & Hall/CRC Press, Boca Raton - London, 2004. ISBN 1-58488-355-3
- A.D. Polyanin, A.M. Kutepov, A.V. Vyazmin, and D.A. Kazenin, *Hydrodynamics, Mass and Heat Transfer in Chemical Engineering*, Taylor & Francis, London, 2002. ISBN 0-415-27237-8
- Herrmann Schlichting, Klaus Gersten, E. Krause, H. Jr. Oertel, C. Mayes "Boundary-Layer Theory" 8th edition Springer 2004 ISBN 3-540-66270-7
- John D. Anderson, Jr, "Ludwig Prandtl's Boundary Layer", *Physics Today*, December 2005
- Anderson, John (1991). *Fundamentals of Aerodynamics*, 2nd edition, Toronto: McGraw-Hill, 711-714. ISBN 0-07-001679-8.

Drag

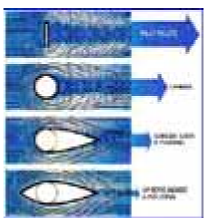


Drag is a resistance force generated by a solid object moving through a fluid.

Any physical body being propelled through the air has drag associated with it. In aerodynamics, drag is defined as the force that opposes forward motion through the atmosphere and is parallel to the direction of the free-stream velocity of the airflow. Drag must be overcome by thrust in order to achieve forward motion.

Drag is generated by nine conditions associated with the motion of air particles over the aircraft. There are several types of drag: form, pressure, skin friction, parasite, induced, and wave.

The term "separation" refers to the smooth flow of air as it closely hugs the surface of the wing then suddenly breaking free of the surface and creating a chaotic flow. The second picture on the left hand margin of this page shows examples of air flowing past a variety of objects. The bottom shows well behaved, laminar flow (flow in layers) where the flow stays attached (close to the surface) of the object. The object just above has a laminar flow for the first half of the object and then the flow begins to separate from the surface and form many chaotic tiny vortex flows called vortices. The two objects just above them have a large region of separated flow. The greater the region of separated flow, the greater the drag. This is why airplane designers go to such effort to streamline wings and tails and fuselages — to minimize drag.



Form or pressure drag is caused by the separation of air that is flowing over the aircraft or airfoil.

Form drag and *pressure drag* are virtually the same type of drag. Form or pressure drag is caused by the air that is flowing over the aircraft or airfoil. The separation of air creates turbulence and results in pockets of low and high pressure that leave a wake behind the airplane or airfoil (thus the name pressure drag). This opposes forward motion and is a component of the total drag. Since this drag is due to the shape, or form of the aircraft, it is also called form drag. Streamlining the aircraft will reduce form drag, and parts of an aircraft that do not lend themselves to streamlining are enclosed in covers called fairings, or a cowling for an engine, that have a streamlined shape. Airplane components that produce form drag include (1) the wing and wing flaps, (2) the fuselage, (3) tail surfaces, (4) nacelles, (5) landing gear, (6) wing tanks and external stores, and (7) engines.

Skin friction drag is caused by the actual contact of the air particles against the surface of the aircraft. This is the same as the friction between any two objects or substances. Because skin friction drag is an interaction between a solid (the airplane surface) and a gas (the air), the magnitude of skin friction drag depends on the properties of both the solid and the gas. For the solid airplane, skin fiction drag can be reduced, and airspeed can be increased somewhat, by keeping an aircraft's surface highly polished and clean. For the gas, the magnitude of the drag depends on the viscosity of the air. Along the solid surface of the airplane, a boundary layer of low energy flow is generated. The magnitude of the skin friction depends on the state of this flow.

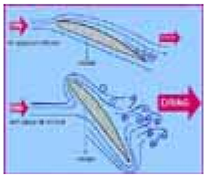
The leading edge of a wing will always produce a certain amount of friction drag.

Parasite drag is simply the mathematical sum of form drag and skin friction drag.

Parasite Drag = Form Drag + Skin Friction Drag

Induced drag is the drag created by the vortices at the tip of an aircraft's wing. *Induced drag* is the drag due to lift. The high pressure underneath the wing causes the airflow at the tips of the wings to curl around from bottom to top in a circular motion. This results in a trailing vortex. Induced drag increases in direct proportion to increases in the angle of attack. The circular motion creates a change in the angle of attack near the wing tip which causes an increase in drag. The greater the angle of attack up to the critical angle (where a stall takes place), the greater the amount of lift developed and the greater the induced drag.

All of these types of drag must be accounted for when determining drag for subsonic flight. The *total drag* is the sum of parasite and induced drag.



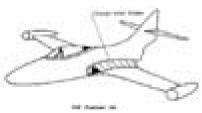
Induced drag is a byproduct of lift.

Total Drag = Parasite Drag + Induced Drag

But the net (or total) drag of an aircraft is not simply the sum of the drag of its components. When the components are combined into a complete aircraft, one component can affect the air flowing around and over the airplane, and hence, the drag of one component can affect the drag associated with another component. These effects are called *interference effects*, and the change in the sum of the component drags is called *interference drag*. Thus,

$$(\text{Drag})_{1+2} = (\text{Drag})_1 + (\text{Drag})_2 + (\text{Drag})_{\text{interference}}$$

Generally, interference drag will add to the component drags but in a few cases, for example, adding tip tanks to a wing, total drag will be less than the sum of the two component drags because of the reduction of induced drag.



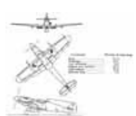
This figure shows a Grumman F9F Panther Jet with a large degree of filleting to reduce drag.

Interference drag can be minimized by proper fairing and filleting, which induces smooth mixing of air past the components. No adequate theoretical method will predict interference drag; thus, wind tunnel or flight-test measurements are required. For rough computational purposes, a figure of 5 percent to 10 percent can be attributed to interference drag on a total aircraft.

Small items also add to the total aircraft drag and, although seemingly trivial, they can greatly reduce the aircraft's top speed.

Although prediction of drag and wind tunnel drag measurements of models yield good results, final drag evaluation must be obtained by flight tests.

Wave drag occurs in supersonic flight, or flight above the speed of sound. Wave drag is a form of pressure drag. When an aircraft breaks the speed of sound, a shock wave is created. A shock wave is a strong pressure wave that creates a violent change in pressure. High pressure pushes on the front of the aircraft. This results in a large pressure drag toward the rear of the aircraft like that produced with form or pressure drag in subsonic flight.



This figure shows a Me-109G German fighter from World War II. Shown is the percentage breakdown of the drag (includes interference drag) of the components.

The airplane's total drag determines the amount of thrust required at a given airspeed. Thrust must equal drag in steady flight.

Lift and drag vary directly with the density of the air. As air density increases, lift and drag increase and as air density decreases, lift and drag decrease. Thus, both lift and drag will decrease at higher altitudes.

The equation used to calculate drag is:

$$D = \tfrac{1}{2} \rho V^2 S C_D$$

Where:

$D=\frac{1}{2}\rho V^2 S C_D$ - the density of the air

V - velocity of the air (air speed)

S -surface area of the aircraft

$D=\frac{1}{2}\rho V^2 S C_D$ - coefficient of drag

Decrease in airplane drag coefficient with time.

The coefficient of drag is calculated based on the angle of attack and shape of the aircraft. The angle of attack is the angle between the direction of the wing (chord line) and the relative wind of the aircraft.

—Dan Johnston

References and Further Reading:

Anderson, Jr., John D. *A History of Aerodynamics*. Cambridge, England: Cambridge University Press, 1997.

Montgomery, Jeff, exec. ed. *Aerospace: The Journey of Flight*. Maxwell Air Force Base, Ala.: Civil Air Patrol: 2000.

Smith, Hubert “Skip.” *The Illustrated Guide to Aerodynamics*. 2nd edition. Blue Ridge Summit, Pa.: Tab Books Inc.1992.

Talay, Theodore A. *Introduction to the Aerodynamics of Flight*. SP-367, Scientific and Technical Information Office, National Aeronautics and Space Administration, Washington, D.C. 1975. Available at http://history.nasa.gov/SP-367/cover367.htm.

Wegener, Peter P. *What Makes Airplanes Fly?* New York: Springer-Verlag, 1991.

“Boundary Layer Separation and Pressure Drag.” University of Virginia Department of Physics. http://www.phys.virginia.edu/classes/311/notes/fluids2/node11.html

“Drag.” Lego Design and Programming System. http://ldaps.ivv.nasa.gov/Physics/drag.html

"Streamlining." http://www.grc.nasa.gov/www/K-12/airplane/stream.html

"Angle of attack." http://wright.grc.nasa.gov/WWW/K-12/airplane/incline.html

"Speed of sound." http://wright.grc.nasa.gov/WWW/K-12/airplane/sound.html

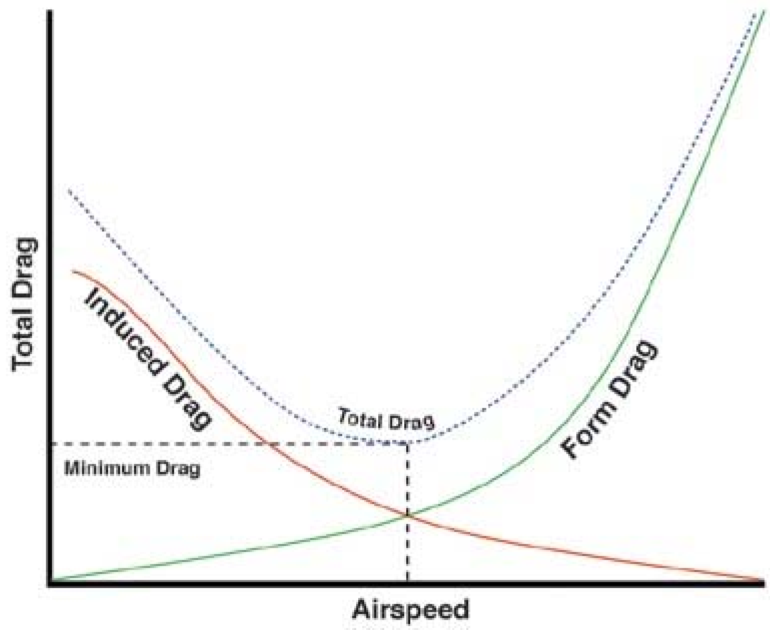
“Shock Waves.” Encyclopedia Britannica. http://www.britannica.com/eb/article?eu=69210&tocid=0&query=shock%20wave. Available on CD, on-line through subscription, and in print version.

“What Is Drag?” NASA Glenn Research Center. http://www.grc.nasa.gov/WWW/K-12/airplane/drag1.html.

Educational Organization	Standard Designation (where applicable	Content of Standard
International Technology Education Association	Standard 2	Students will develop an understanding of the core concepts of technology.
National Council of Teachers of Mathematics	N/A	Understand the value and use of mathematical language.
National Council of Teachers of Mathematics	N/A	Understand numbers, ways of representing numbers, relationships among numbers, and number systems.
American Association for the Advancement of Science	N/A	Understand principles of motion and forces

Parasitic drag

From Wikipedia, the free encyclopedia
(Redirected from Skin friction)



Parasitic drag (also called **parasite drag**) is drag caused by moving a solid object through a fluid. Parasitic drag is made up of many components, the most prominent being **form drag**. **Skin friction** and **interference drag** are also major components of parasitic drag.

In aviation, induced drag tends to be greater at lower speeds because a high angle of attack is required to maintain lift, creating more drag. However, as speed increases the induced drag becomes much less, but parasitic drag increases because the fluid is flowing faster around protruding objects increasing friction or drag. At even higher speeds in the transonic, wave drag enters the picture. Each of these forms of drag changes in proportion to the others based on speed. The combined overall drag curve therefore shows a minimum at some airspeed - an aircraft flying at this speed will be at or close to its optimal efficiency. Pilots will use this speed to maximize endurance (minimum fuel consumption), or maximise gliding range in the event of an engine failure.

Contents

Form drag

Form drag, **profile drag**, or **pressure drag**, arises because of the form of the object. The general size and shape of the body is the most important factor in form drag - bodies with a larger apparent cross-section will have a higher drag than thinner bodies. Sleek designs, or designs that are streamlined and change cross-sectional area gradually are also critical for achieving minimum form drag. In some cases, cooling systems can be a serious source of drag, and Evaporative cooling was developed to remedy that. Form drag follows the drag equation, meaning that it rises with the square of speed, and thus becomes more important for high speed aircraft.

Profile Drag (Pxp): depends on the longitudinal section of the body. A diligent choice of body profile is more than essential for low drag coefficient. Streamlines should be continuous and separation of the boundary layer with its attendant vortices should be avoided.

Interference drag

Interference drag arises from vortices. Whenever two surfaces meet at a sharp angle on an airplane, the airflow has a tendency to form a vortex. Accelerating the air into this vortex causes drag on the plane, and the resulting low pressure area behind the plane also contributes. Thus, the primary method of reducing interference drag is eliminating sharp angles by adding fairings which smooth out any sharp angles on the aircraft by forming fillets. Interference drag is also created by closely spaced parallel surfaces such as the wings of a biplane or triplane, or the facing surfaces of an external load (such as an external fuel tank or weapon) and the fuselage or wing. As with other components of parasitic drag, interference drag follows the drag equation and rises with the square of the velocity.

Skin friction

Skin friction arises from the friction of the fluid against the "skin" of the object that is moving through it. Skin friction is a function of the interaction between the fluid and the skin of the body, as well as the wetted surface, or the area of the surface of the body that would become wet if sprayed with water flowing in the wind. As with other components of parasitic drag, skin friction follows the drag equation and rises with the square of the velocity.

Skin friction is caused by viscous drag in the boundary layer around the object. The boundary layer at the front of the object is usually laminar and relatively thin, but becomes turbulent and thicker towards the rear. The position of the transition point depends on the Reynolds number of the object.[1]

References

1. ^ [1]

U.S. Centennial of Flight Commission

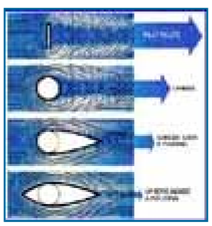
Drag

Drag is a resistance force generated by a solid object moving through a fluid.

Any physical body being propelled through the air has drag associated with it. In aerodynamics, drag is defined as the force that opposes forward motion through the atmosphere and is parallel to the direction of the free-stream velocity of the airflow. Drag must be overcome by thrust in order to achieve forward motion.

Drag is generated by nine conditions associated with the motion of air particles over the aircraft. There are several types of drag: form, pressure, skin friction, parasite, induced, and wave.

The term "separation" refers to the smooth flow of air as it closely hugs the surface of the wing then suddenly breaking free of the surface and creating a chaotic flow. The second picture on the left hand margin of this page shows examples of air flowing past a variety of objects. The bottom shows well behaved, laminar flow (flow in layers) where the flow stays attached (close to the surface) of the object. The object just above has a laminar flow for the first half of the object and then the flow begins to separate from the surface and form many chaotic tiny vortex flows called vortices. The two objects just above them have a large region of separated flow. The greater the region of separated flow, the greater the drag. This is why airplane designers go to such effort to streamline wings and tails and fuselages — to minimize drag.



Form or pressure drag is caused by the separation of air that is flowing over the aircraft or airfoil.

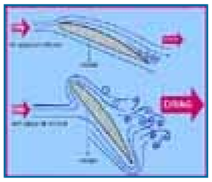
Form drag and *pressure drag* are virtually the same type of drag. Form or pressure drag is caused by the air that is flowing over the aircraft or airfoil. The separation of air creates turbulence and results in pockets of low and high pressure that leave a wake behind the airplane or airfoil (thus the name pressure drag). This opposes forward motion and is a component of the total drag. Since this drag is due to the shape, or form of the aircraft, it is also called form drag. Streamlining the aircraft will reduce form drag, and parts of an aircraft that do not lend themselves to streamlining are enclosed in covers called fairings, or a cowling for an engine, that have a streamlined shape. Airplane components that produce form drag include (1) the wing and wing flaps, (2) the fuselage, (3) tail surfaces, (4) nacelles, (5) landing gear, (6) wing tanks and external stores, and (7) engines.

The leading edge of a wing will always produce a certain amount of friction drag.

Skin friction drag is caused by the actual contact of the air particles against the surface of the aircraft. This is the same as the friction between any two objects or substances. Because skin friction drag is an interaction between a solid (the airplane surface) and a gas (the air), the magnitude of skin friction drag depends on the properties of both the solid and the gas. For the solid airplane, skin fiction drag can be reduced, and airspeed can be increased somewhat, by keeping an aircraft's surface highly polished and clean. For the gas, the magnitude of the drag depends on the viscosity of the air. Along the solid surface of the airplane, a boundary layer of low energy flow is generated. The magnitude of the skin friction depends on the state of this flow.

Parasite drag is simply the mathematical sum of form drag and skin friction drag.

Parasite Drag = Form Drag + Skin Friction Drag

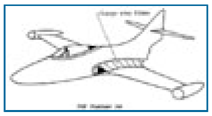


Induced drag is a byproduct of lift.

Induced drag is the drag created by the vortices at the tip of an aircraft's wing. *Induced drag* is the drag due to lift. The high pressure underneath the wing causes the airflow at the tips of the wings to curl around from bottom to top in a circular motion. This results in a trailing vortex. Induced drag increases in direct proportion to increases in the angle of attack. The circular motion creates a change in the angle of attack near the wing tip which causes an increase in drag. The greater the angle of attack up to the critical angle (where a stall takes place), the greater the amount of lift developed and the greater the induced drag.

All of these types of drag must be accounted for when determining drag for subsonic flight. The *total drag* is the sum of parasite and induced drag.

Total Drag = Parasite Drag + Induced Drag



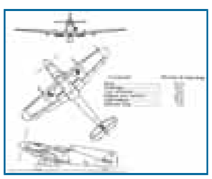
This figure shows a Grumman F9F Panther Jet with a large degree of filleting to reduce drag.

But the net (or total) drag of an aircraft is not simply the sum of the drag of its components. When the components are combined into a complete aircraft, one component can affect the air flowing around and over the airplane, and hence, the drag of one component can affect the drag associated with another component. These effects are called *interference effects*, and the change in the sum of the component drags is called *interference drag*. Thus,

$$(\text{Drag})_{1+2} = (\text{Drag})_1 + (\text{Drag})_2 + (\text{Drag})_{\text{interference}}$$

Generally, interference drag will add to the component drags but in a few cases, for example, adding tip tanks to a wing, total drag will be less than the sum of the two component drags because of the reduction of induced drag.

Interference drag can be minimized by proper fairing and filleting, which induces smooth mixing of air past the components. No adequate theoretical method will predict interference drag; thus, wind tunnel or flight-test measurements are required. For rough computational purposes, a figure of 5 percent to 10 percent can be attributed to interference drag on a total aircraft.



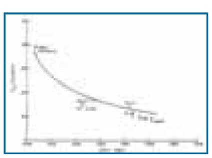
This figure shows a Me-109G German fighter from World War II. Shown is the percentage breakdown of the drag (includes interference drag) of the components.

Small items also add to the total aircraft drag and, although seemingly trivial, they can greatly reduce the aircraft's top speed.

Although prediction of drag and wind tunnel drag measurements of models yield good results, final drag evaluation must be obtained by flight tests.

Wave drag occurs in supersonic flight, or flight above the speed of sound. Wave drag is a form of pressure drag. When an aircraft breaks the speed of sound, a shock wave is created. A shock wave is a strong pressure wave that creates a violent change in pressure. High pressure pushes on the front of the aircraft. This results in a large pressure drag toward the rear of the aircraft like that produced with form or pressure drag in subsonic flight.

The airplane's total drag determines the amount of thrust required at a given airspeed. Thrust must equal drag in steady flight.



Lift and drag vary directly with the density of the air. As air density increases, lift and drag increase and as air density decreases, lift and drag decrease. Thus, both lift and drag will decrease at higher altitudes.

The equation used to calculate drag is:

Decrease in airplane drag coefficient with time.

$$D = \frac{1}{2} \rho V^2 S C_D$$

Where:

$D = \frac{1}{2} \rho V^2 S C_D$ - the density of the air

V - velocity of the air (air speed)

S -surface area of the aircraft

$D = \frac{1}{2} \rho V^2 S C_D$ - coefficient of drag

The coefficient of drag is calculated based on the angle of attack and shape of the aircraft. The angle of attack is the angle between the direction of the wing (chord line) and the relative wind of the aircraft.

—Dan Johnston

References and Further Reading:

Anderson, Jr., John D. *A History of Aerodynamics*. Cambridge, England: Cambridge University Press, 1997.

Montgomery, Jeff, exec. ed. *Aerospace: The Journey of Flight*. Maxwell Air Force Base, Ala.: Civil Air Patrol: 2000.

Smith, Hubert "Skip." *The Illustrated Guide to Aerodynamics*. 2nd edition. Blue Ridge Summit, Pa.: Tab Books Inc.1992.

Talay, Theodore A. *Introduction to the Aerodynamics of Flight*. SP-367, Scientific and Technical Information Office, National Aeronautics and Space Administration, Washington, D.C. 1975. Available at http://history.nasa.gov/SP-367/cover367.htm.

Wegener, Peter P. *What Makes Airplanes Fly?* New York: Springer-Verlag, 1991.

"Boundary Layer Separation and Pressure Drag." University of Virginia Department of Physics. http://www.phys.virginia.edu/classes/311/notes/fluids2/node11.html

"Drag." Lego Design and Programming System. http://ldaps.ivv.nasa.gov/Physics/drag.html

"Streamlining." http://www.grc.nasa.gov/www/K-12/airplane/stream.html

"Angle of attack." http://wright.grc.nasa.gov/WWW/K-12/airplane/incline.html

"Speed of sound." http://wright.grc.nasa.gov/WWW/K-12/airplane/sound.html

"Shock Waves." Encyclopedia Britannica. http://www.britannica.com/eb/article?eu=69210&tocid=0&query=shock%20wave. Available on CD, on-line through subscription, and in print version.

“What Is Drag?” NASA Glenn Research Center. http://www.grc.nasa.gov/WWW/K-12/airplane/drag1.html.

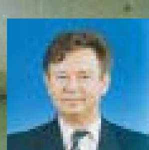
Educational Organization	Standard Designation (where applicable	Content of Standard
International Technology Education Association	Standard 2	Students will develop an understanding of the core concepts of technology.
National Council of Teachers of Mathematics	N/A	Understand the value and use of mathematical language.
National Council of Teachers of Mathematics	N/A	Understand numbers, ways of representing numbers, relationships among numbers, and number systems.
American Association for the Advancement of Science	N/A	Understand principles of motion and forces

GETTING HANDS-ON EXPERIENCE WITH AERODYNAMIC DETERIORATION

This article is an extract of a brochure of the same name which covers the complete Airbus aircraft family.

Today's tough competitive environment forces airlines to reduce their operational costs in every facet of their business. Every method to achieve this goal has to be envisaged, safety and accident prevention permitting of course, as these are prime factors in any aircraft operation. A wide variety of different aspects have to be taken into account in this process, such as Air Traffic Control, engine deterioration, flight operations management, instrument accuracy or aero-dynamic deterioration.

The purpose of this document is to examine the influence of aerodynamic de-terioration.



by Jean-Jacques Speyer
Manager Operational Evaluation
Flight Operations Support
Airbus Industrie
Customer Services Directorate

The manufacturer does its best from the development phase onwards to foresee all potential deteriorations and adopt designs which are the least sensitive to in-service deterioration and by continuous research and modification programmes, to keep the aircraft deterioration processes within acceptable bounds. The operator's responsibility is to maintain his aircraft in good condition and make sure that it is utilised in the most satisfactory conditions possible.

Unfortunately, in the life of an aircraft , degradation is likely to occur. An aircraft is normally expected to increase its drag by up to 2% within five years if not properly maintained. Indeed, many aerodynamic elements may increase drag and their cumulative effect can introduce a significant cost increase. Simply adopting corrective action in order to repair these items, could lead to excessive maintenance costs. Therefore, the effect of deterioration has to be traded-off against the estimated maintenance cost, in order to check whether it is cost-effective to carry out corrective measures. Cost-benefit analysis is the only practical way of keeping an aircraft operationally efficient.

Airbus Industrie has carried out numerous performance audits in co-operation with airlines which, implicitly, have made a very useful contribution to this document.

The information in this document will help the aircraft operator adapt its maintenance programme, balancing financial aspects, such as increased fuel consumption against maintenance costs. It should enable operators to determine whether corrective actions are financially pertinent, despite short-term maintenance costs. Considerable longer-term expense may thus be avoided at relatively low cost. And strategic maintenance actions rather than detailed, dispersed and costly repair jobs may be more easily decided upon and justified.

GENERAL

Aerodynamic deterioration

Some of the most severe penalties in terms of fuel consumption are caused by increased drag resulting from poor airframe condition. Normal aerodynamic deterioration of an aircraft over a period of time can include the incomplete retraction of moving surfaces, damaged seals on control surfaces, skin roughness and deformation due to bird strikes or damage caused by ground vehicles, chipped paint, mismatching doors and excessive gaps. All these items are potential money wasters. Each deterioration incurs drag increase, and this increased drag is accompanied by increased fuel consumption.

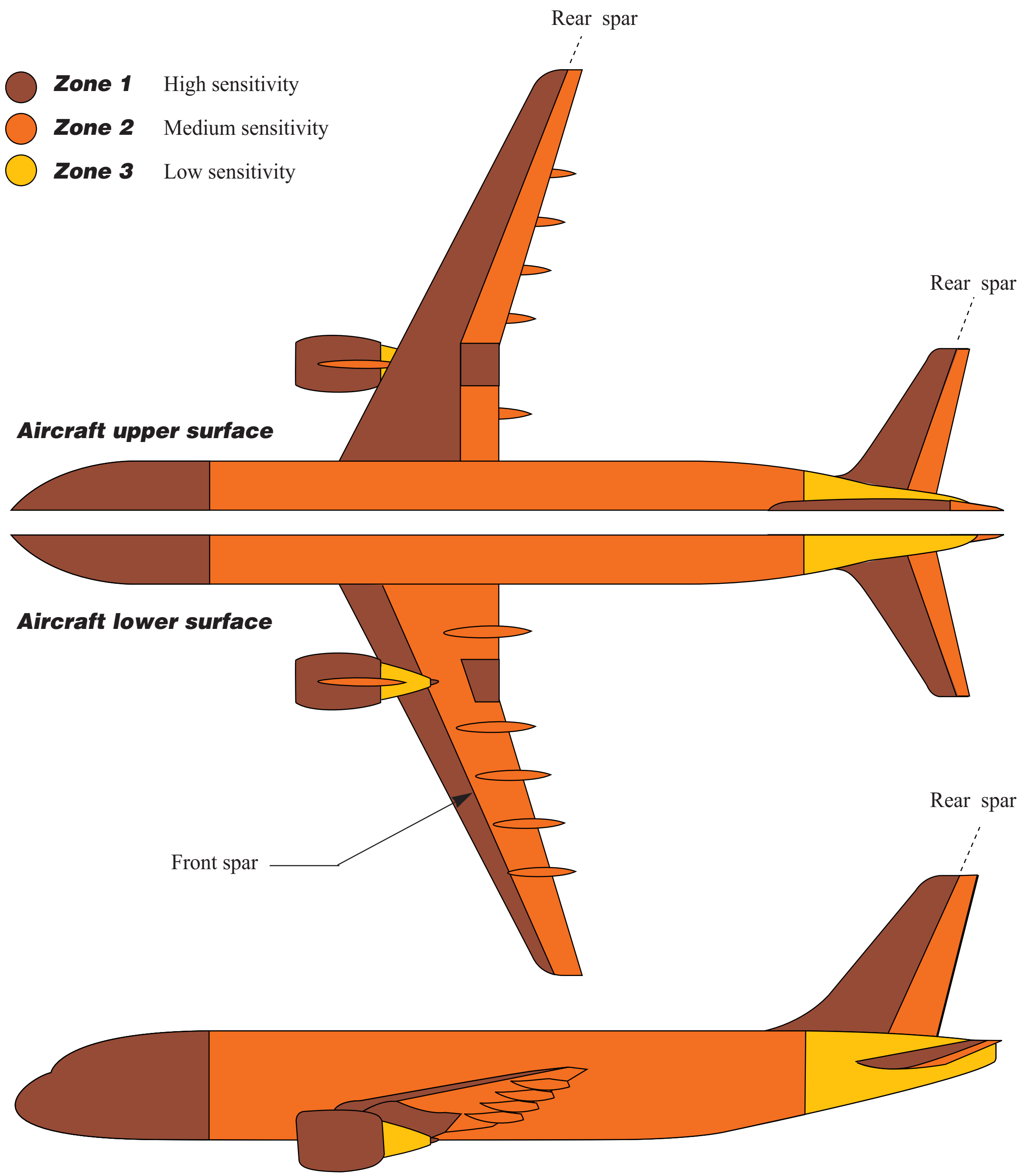
Sensitivity classification

The fuel burn penalty caused by drag-inducing items is largely dependent upon the location and extent of the problem; different areas of the airframe are more or are less sensitive to alterations in their optimum aerodynamic smoothness. Bearing this in mind, a zonal classification can be established for drag sensitivity over the whole aircraft (see Figure 1).

Zone 1 surfaces require high aerodynamic smoothness because they are endowed with high local flow velocities and very thin boundary layers which are very sensitive to small local disturbance. Zone 3 surfaces are much less sensitive because of lower flow veloci-

Figure 1

Drag sensitivity zones (A300/A310)



ties and thicker boundary layers, and disturbance on these parts of the airframe does not produce high aerodynamic resistance to the airflow. Also, the transition from laminar to turbulent boundary layers having occurred earlier, zone 3 is less sensitive to aerodynamic irregularities or excrescences. Finally, zone 2 surfaces represent an average between these two extremes.

The localisation of zones 1, 2 and 3 for A300/A310 are shown in the figure 1. The zones differ slightly for the other Airbus aircraft.

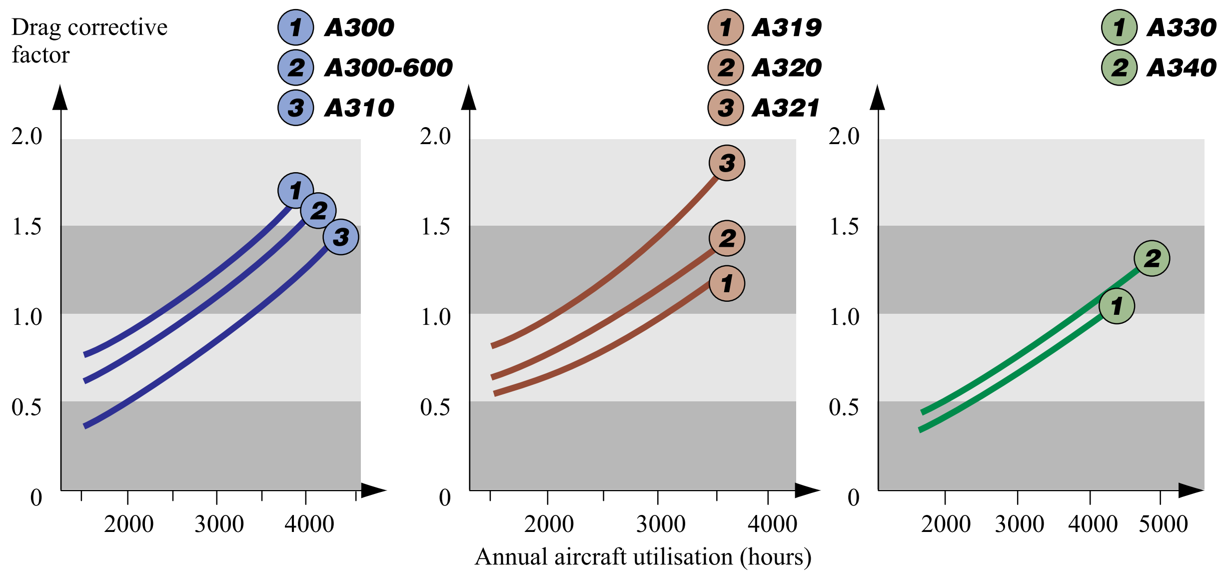
Fuel penalty calculation

It is possible to determine drag increase, generated by particular items, with wind-tunnel measurements or analytical techniques. The drag increase is then converted into terms of increased fuel burn - in US gallons per year per aircraft - but the reader must keep in mind that the values given correspond to an aircraft which is in accordance with specific assumptions. These assumptions refer to each type of aircraft of the three Airbus families and include annual flight hours based on airline statistics.

The drag increase can also be expressed in US$ per year per aircraft, the fuel price being based at US$0.60 per gallon. Note: fuel prices have increased by about 30% in the last year. Since calculation assumptions may vary significantly among individual operators, tables giving a corrective factor - to apply to the fuel penalty to be derived from the operator's annual flight hours - is given for each type of aircraft, in Figure 2.

Figure 2

Corrective factor for drag penalty



Airframe maintenance

For a specific corrective task, manhours required can significantly vary from one airline to another, and from one type of repair to another. The calculation method adopted in this document is simply an estimation partly based on measurements. These tasks should have been carried out assuming a regularly maintained aircraft, operated under normal conditions and with an average daily utilisation, having maintenance /corrective actions carried out in a hangar with good environmental conditions. All necessary standard and special tools, as well as ground support equipment, skilled maintenance personnel and appropriate maintenance documentation should also be available.

The values presented herein (men and manhours) are based on these assumptions and are intended to reflect operational reality as closely as possible.

Total maintenance costs, for both on-aircraft and shop tasks, include overhead and burden costs for maintenance planning, engineering orders, safety equipment, facilities and supervision. An acceptable rate per manhour covering all these aspects is US$50. Serving as a benchmark, this value corresponds to an average cost covering skilled working personnel.

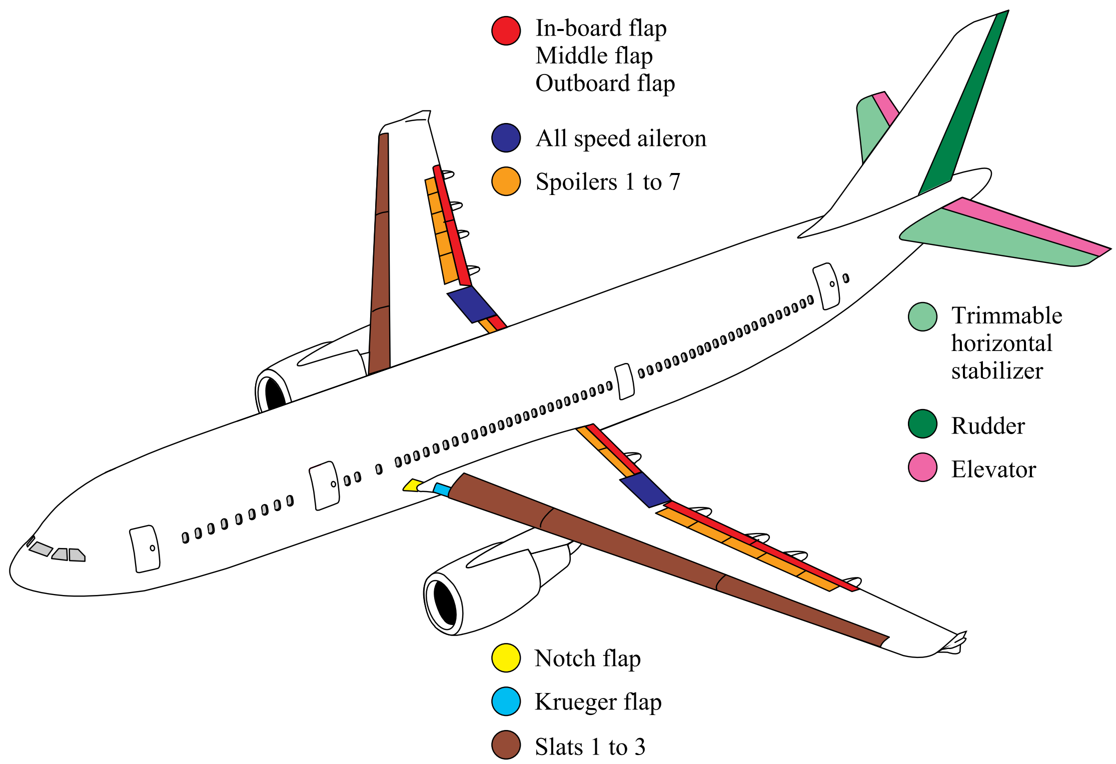
Adapted maintenance programme

As stated above, the degradations that are likely to occur stem from two main sources (excluding incidents or handling) : either mechanical wear or corrective actions which have not been properly executed. Although ill-considered or superficial repair may have negligible effect on performance, some tasks have to be carried out with special care, given their positive impact on fuel consumption.

As mentioned before, despite the efforts of maintenance organisations and manufacturers, deterioration can occur. It may have significant effects on consumption in spite of having only a slight influence on drag. One way to determine these effects is to use the Aircraft Performance Monitoring (APM) software. This programme calculates deviations in Specific Range and, to some extent, helps to determine how much these discrepancies stem from engine degradation and how much from a lack of aerodynamic cleanliness. Inherently, the program does not really differentiate between apparent and real drag.

Figure 3

Flying control surfaces



For instance, higher drag may be concluded from APM results but could, in fact, reflect lower thrust at N1 (or EPR). Also bleed leaks can affect apparent aerodynamic deterioration through N1 deviations by biasing the N1/thrust relationship if they are not accounted for. For these reasons, values given by the APM software have to be considered with great care.

Nevertheless, they can trigger an alarm at a predetermined loss of Specific Range in relation to the initial aircraft drag condition, and an unscheduled check could be launched to detect the type and location of any drag rise. This unscheduled check could be a line check walkaround associated with an overwing in-flight check observing and photographing control surfaces, preferably by means of a telephoto or zoom lens. The association of both types of check constitutes an Aerodynamic Inspection. The items to be observed are shown in Figure 3. This Aerodynamic Inspection, which would take only a short time to perform, should be done by skilled personnel as for example aerodynamics or performance engineers, able to interpret secondary effects (e.g. leakages) and to determine the corresponding deviations (as well as being able to conduct performance audits).

When both the type and extent of the deterioration are known, the following tables (example shown on Figure 4 on the following page)could be used to determine what should be repaired and what may be ignored, for financial reasons. Repair times should be scheduled during night-time periods, time permitting, otherwise the task has to be included in a scheduled check.

The Aircraft Performance Monitoring software has the advantage of potentially triggering an Aerodynamic Inspection just when it is needed, thus avoiding unnecessary inspection.

If the APM software is not used, the Aerodynamic Inspection could be scheduled, for instance, at the occasion of a “C check”.

Although this approach may confirm discrepancies, not all may be identified. In this case direct measurements in the suspected area should be made, such as prescribed in the Aircraft Maintenance Manual. This second way is more expensive but it may offer better drag reduction results.

In a third stage, if the drag reduction seems insufficient, the airline may then ask Airbus Industrie for a Performance Audit.

These three approaches should help any airline to alleviate excessive fuel consumption.

Figure 4

Cost of misrigged flying control surfaces (A300/A310)

Control surface	Penalty in US$ gallons per year Excess gap 5mm	10mm	15mm	Penalty in US$ per year Excess gap 5mm	10mm	15mm	Aircraft Maintenance Manual	Corrective action Men	M/h	Cost (US$)
Slat 1 (per metre)	3,850	6,100	9,150	2,310	3,660	5,490	27 80 00 27 81 00	2	5	250
Slat 2 (per metre)	5,190	8,220	12,330	3,110	4,930	7,400	27 80 00 27 81 00	2	5	250
Slat 3 (per metre)	7,700	12,200	18,300	4,620	7,320	10,980	27 80 00 27 81 00	2	5	250
Flap	810	1,490	2,060	490	890	1,230	27 51 00 27 54 00	2	6	300
Spoiler	3,060	6,850	10,220	1,840	4,110	6,130	27 61 00 27 62 00	1	2	100
Aileron	810	1,500	2,120	490	900	1,270	27 11 00	1	3	150
Rudder	1,350	2,350	3,550	810	1,410	2,130	27 21 00 27 24 00	2	4	200
Misalignment at flap track fairing	680	1,360	1,700	410	820	1,020	05 25 30	2	5	250

DETERIORATION OF AIRFRAME AND SURFACES

The purpose of the following is to give a fuel penalty and maintenance cost comparison for the items studied.

Values given in this particular section correspond to the smaller fuel penalties applicable to all Airbus Industrie aircraft. They are intended to make the reader more sensitive to fuel penalties / maintenance cost comparison and to sort out a few general conclusions which pertain to all Airbus Industrie aircraft.

Misrigging of control surfaces.

These items correspond to specific control surfaces misrigging (see Figure 5). They incur one of the largest fuel penalties, while the cost of the corrective actions, by comparison, is negligible. Indeed, one spoiler extended by 15mm over a 1 metre spanwise length leads to more than US$ 6,000 penalty per aircraft per year (see Figure 4 above). Similarly, an outboard slat misrigging causes nearly US$ 11,000 penalty per aircraft per year. Furthermore, flap misrigging - or especially rudder misrigging - can lead to a slightly lower, but still considerable, fuel penalty. Another sensitive item which is generally forgotten is misalignment at a flap track fairing which may cost nearly US$ 1,000 per aircraft per year.

The Aerodynamic Inspection could be done in flight, simply by a visual inspection from the passenger compartment and by photographing control surfaces by means of a telephoto or zoom lens.

For a misrigged control surface, the associated corrective action cost is negligible and should indeed be undertaken.

Absence of seals on movable sections

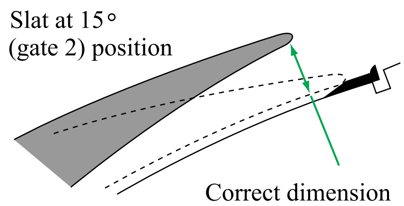
Seals on movable sections are very important and should not be forgotten. The spanwise slat seals are mandatory for the optimisation of the wing supercritical airfoil. One metre of missing seal incurs a penalty of US$ 2,300 per aircraft per year. The chordwise flap seal, which may seem to have a rather negligible effect, causes more than US$ 3,000 extra cost per aircraft per year. However, the worst penalty would result from a missing fairing

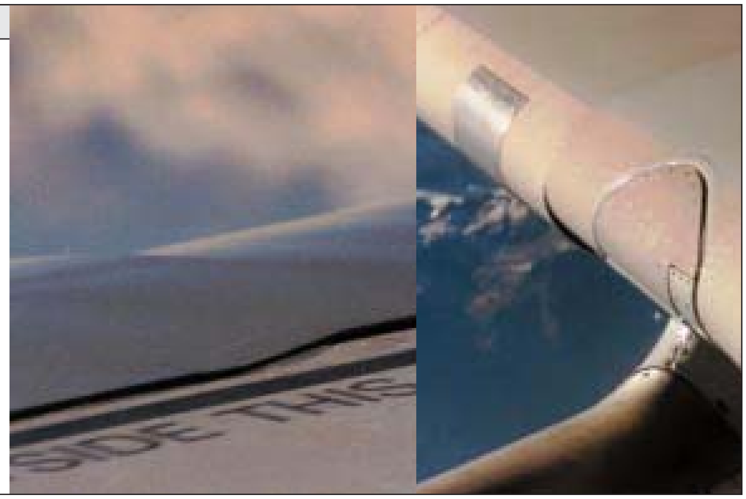
Damaged chordwise flap seal

Figure 5

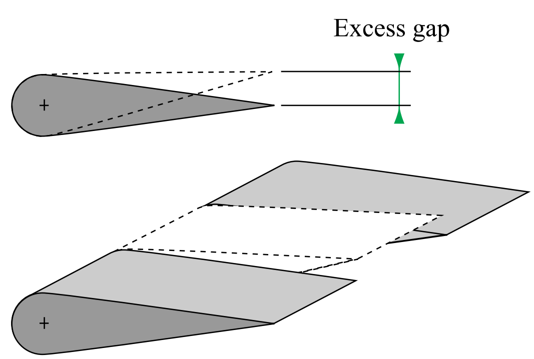
Misrigging of control surfaces

Slat

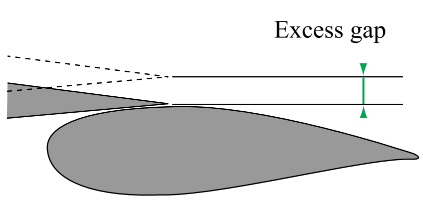


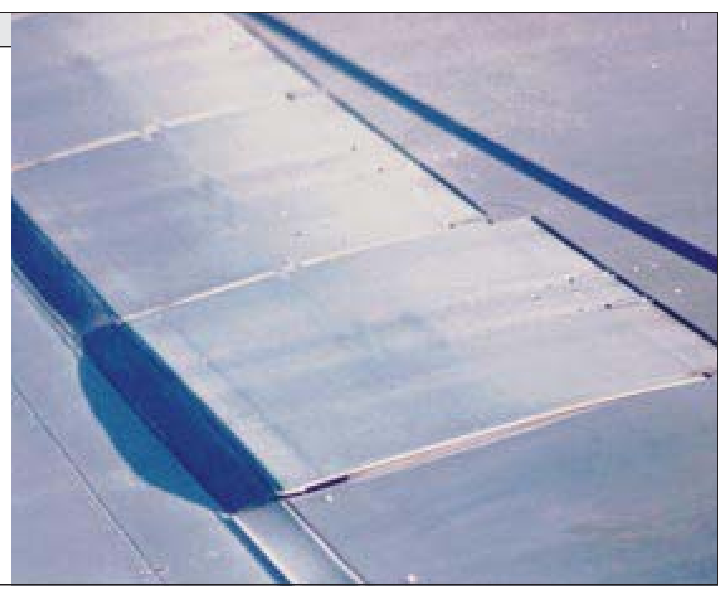


Flap, aileron, rudder



Spoiler





and rubber seal at the fin/fuselage junction (US$ 3,500).

The check can be done from the ground during the Aerodynamic Inspection, preferably with extended control surfaces. With retracted control surfaces, the same check could be done by analysing leakage traces on the wing surface below the seals.

The associated corrective action costs are negligible and such action should be scheduled.

Missing parts

Missing parts are given in the Configuration Deviation List showing missing parts which must be replaced as soon as possible. A missing access door can cost over US$ 6,000 per year which provides adequate motivation to minimise the period of loss.

Mismatched doors

Mismatched access door

A step on the forward fuselage surface is much more penalising than one on the rear. Misalignment of forward doors must be monitored very carefully; a 10mm forward cargo door step imposes a US$ 2,300 annual penalty, although the associated corrective action costs US$ 650.

During the Aerodynamic Inspection, the door can be checked by standing under it and observing the line where it meets the fuselage. Due to pressurisation, the cabin door must be slightly out of flush with the fuselage. In other words, the door must be 2-3 mm inside the fuselage when checked on the ground (see Maintenance Manual).

The decision - to repair or not - is not easy, knowing that an estimated rigging cost could be much higher, especially if insufficiently skilled personnel are available.

The decision is a matter of judgement by each operator.

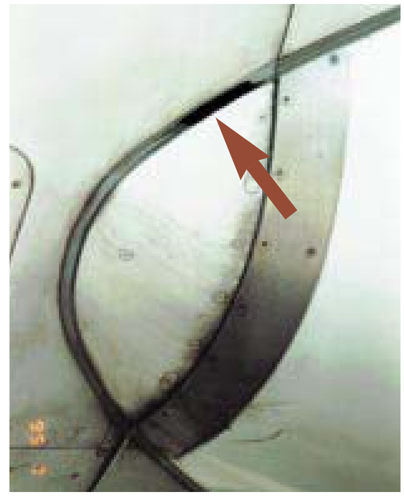
Missing door seal section

A missing door seal section has two effects: it disturbs the external flow and causes a slight leakage which has to be compensated for by an increase in engine compressor air bleed. In addition to the fuel penalty, a stress-provoking low-frequency whistling sound is audible in the cabin which could possibly annoy passengers.

Preferably, the inspection should be done with the door opened, looking for damaged sections of the seal. With a closed door, the same verification could be done simply by analysing dirt traces on the fuselage.

Since this leakage may increase with time, even if corrective actions are quite expensive, this work should be implemented to remove the risk of further deterioration which would lead to the aircraft being grounded eventually.

Missing seal

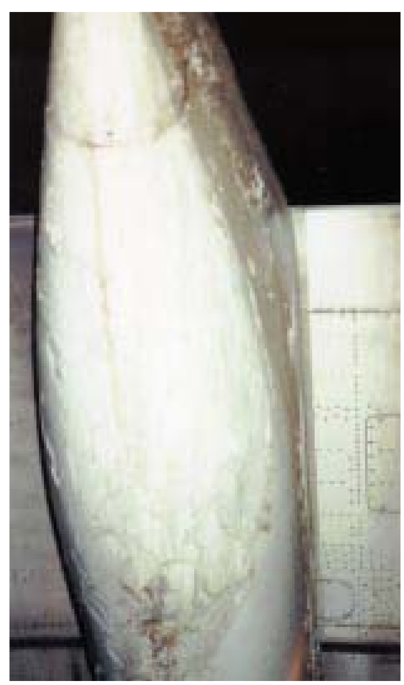


Surface deterioration

Skin roughness

Surface deterioration can lead to significant fuel penalties, especially if the skin is rough or dirty. For a complete aircraft - in the worst case - the penalty can be as high as US$ 60,000 per aircraft per year. Another serious penalty would certainly be on the airline's commercial image!

Skin roughness



Skin dents

Simple dents also cause some fuel penalty which are not costly in terms of fuel consumption (US$ 100 per aircraft per year in the worst case) but are very expensive to repair. If the dent is within the Structural Repair Manual tolerances, no action is necessary for purely aerodynamic reasons.

With repeated «loaders' assaults», scuff plates are frequently dented and generally present a step, generating high fuel penalties, but corrective actions are not particularly time-consuming.

Unfilled butt joint gap

Unfilled butt joint gaps in aircraft skins are not very expensive in terms of excess fuel consumption (US$22 per aircraft per year in the worst case).

CONSEQUENCES OF HASTY REPAIRS

Sometimes, in an operational environment, the purpose of a repair is simply to keep the aircraft in service and to avoid grounding it. Repairs may have been done without taking into account the consequences of increased fuel consumption.

Overfilled butt joint gap

If a butt joint gap is overfilled, the penalty can be significant on the wing upper surface (US$330). A repair which is not properly carried out can lead to a heavier fuel penalty than existed prior to the repair (from US$14 per aircraft per year for an unfilled butt joint gap to US$500 for an overfilled gap on the upperwing in the sensitive zone 1).

External repairs

In the same way, external patches induce more drag, especially on the wing upper surface (US$640). It is normally difficult to replace an external patch by an internal one, but if access has already been gained during an inspection, installing an internal patch could be preferable, since it also has less impact on an airline's commercial image.

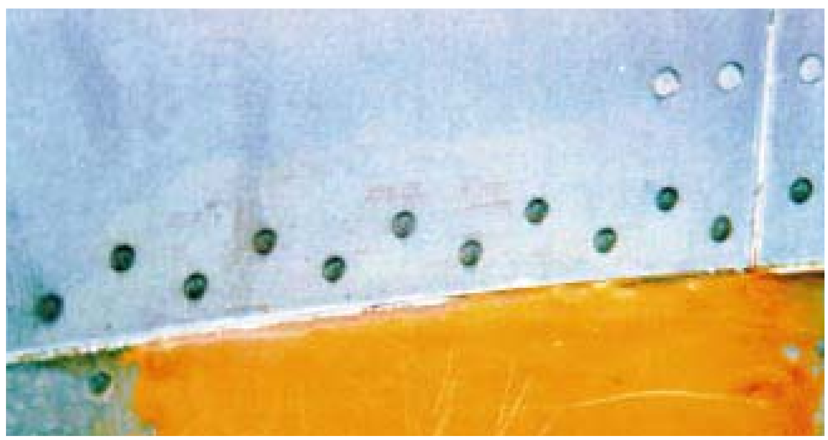
Paint peeling

On the other hand, for visually improving the commercial image, some fleets are often hastily repainted without bothering to properly prepare the surface. Additional paint layers cause increased aircraft weight and the surface is less smooth due to paint steps. Over a short time, paint may peel, with dramatic drag effects, and severe risk of corrosion.

In order to prevent paint problems, proper preparation has to be carried out before any refresher coat is applied.

Manhours for painting have also to be determined with great care because ground time due to paint drying has much more effect on aircraft operation than the simple manhour cost by itself.

Dented scuff plates



External repair

Paint peeling

ENGINE COWLING

The engine cowling, due to its location in a very sensitive zone, has to be observed with great care during the Aerodynamic Inspection.

All surface discrepancies incur considerable drag .

Another item, which is less obvious because it is hidden, is the reverser door seal. The associated fuel penalty is very large and it can be observed by leakages on the engine cowling.

CONCLUSION

The purpose of presenting the foregoing examples is simply to make operators and maintenance personnel more aware of drag-induced performance degradation on normal day-to-day operation.

Manhours for structural repairs must be determined with great care because significant differences exist, mainly depending upon the exact location of the deterioration. All these discrepancies can be observed very easily from the ground during the Aerodynamic Inspection.

It has been shown that many, but not all, aerodynamic degradations can be easily detected and cost-effectively repaired. The Aerodynamic Inspection will identify all of these degradations.

It ultimately becomes a matter of judgement for the airline to decide whether to rectify a fault or to ignore its effect. Nevertheless, all maintenance and operations personnel should be aware of fuel penalties which may stem from misrigged control surfaces, defective seals and the lack or aircraft cleanliness - especially at or near leading edges and forward sections of the aircraft.

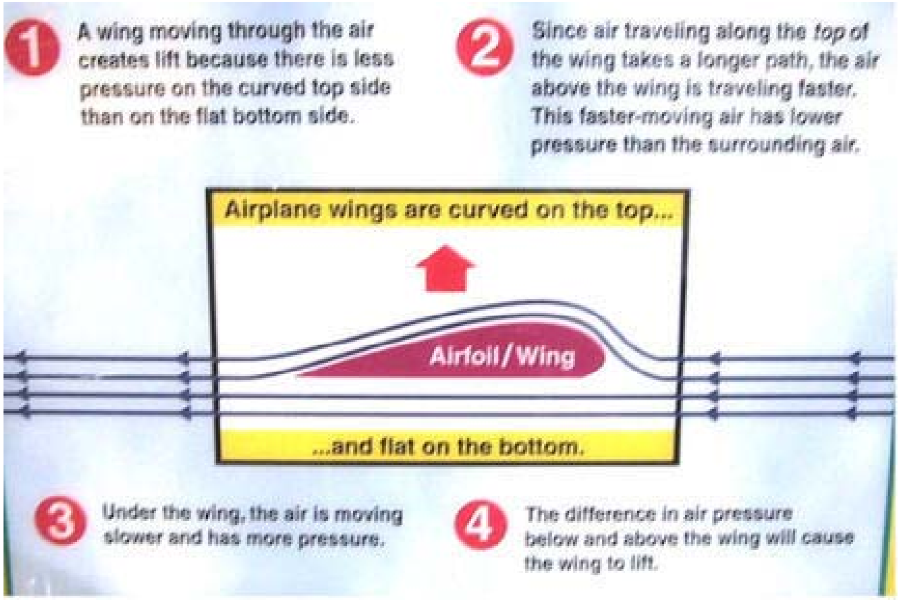
Airbus Industrie is convinced that prevention is better than repair. Continuously monitoring aircraft aerodynamic efficiency, together with timely rectification of problems, is, without a doubt, the best approach to minimising unnecessary fuel consumption. ■

For copies of the complete document, please contact AIRBUS INDUSTRIE headquarters, Customer Services Directorate, Flight Operations Support Department, Mr Jean-Jacques Speyer, Manager Operational Evaluation
1, rond-point Maurice Bellonte, 31707 BLAGNAC Cedex - Tel: +33 (0)5 61 93 30 02 / 30 91 - Fax: +33 (0)5 61 93 29 68 / 44 65

STOP ABUSING BERNOULLI!
LEARN HOW WINGS REALLY WORK--

The driver was seen to stop before each weigh station and beat the side of the truck. When questioned about his strange behavior, he replied: "My truck is overweight with a load of birds. When I beat the truck they fly around so as to take their weights off the perches. Then I can pass the weight check."

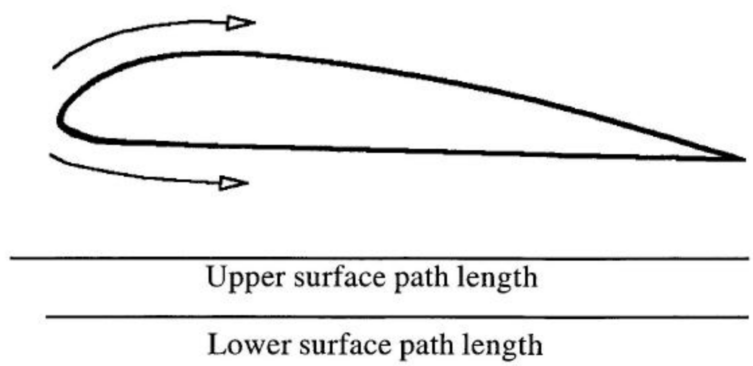
If the next illustration, from an Indianapolis Children's Museum exhibit, is correct, then the driver's strategy might work.



Unfortunately,the above illustration violates the law of conservation of momentum. Merging flows at the rear should maintain downward momentum. Also the principle of action-reaction, which would require upward lift to be equaled by downward accelerative force on the air, is not evidenced in departing air which has no net deflection.

During most of the 20th century, much of the popular teaching of how wings work has been false. In part this has been deliberate. Dr. Theodore Von Karman, a most prominent aerodynamicist in mid-20th century, once told his assistant: "When you are speaking to technically illiterate people you must resort to the plausible falsehood instead of the difficult truth." (from *Stories of a 20th Century Life* by William Reese Sears. This attitude, of course, would require the speaker to judge the listener's technical literacy or lack thereof. In any case, a lie is not a good substitute for true teaching.

Plausible falsehood is still being taught. The most popular theory of wing operation, which we may call *Hump Theory,* because it requires a wing to have a more convex upper surface as compared to the lower, is easily shown to be false. Hump theory is based on *Bernoulli's law,* according to which pressure and velocity are inversely related, and on a *principle of equal transit times,* according to which air passage over an upper wing surface must occur in the same time as air passage below. In order to have the same transit time, flow at a more curved upper wing surface, having a longer path, is said to be of greater velocity than that at a less curved lower surface, making upper surface pressure less than that at the lower, in accordance with Bernoulli's law.



Upper surface flow is indeed faster than the lower, so much so that transit time at the upper surface in typical normal flight is always *LESS* than at the lower. Although Bernoulli's law is sound and well proven, the premise of equal transit time is invalid and without foundation in known physics. Thus the most popular explanation, world-wide, of wing operation is false, and easily shown to be so.

The falsehood is not due to Bernoulli's law, which is well proven, but rather due to falseness of the principle of equal transit times.

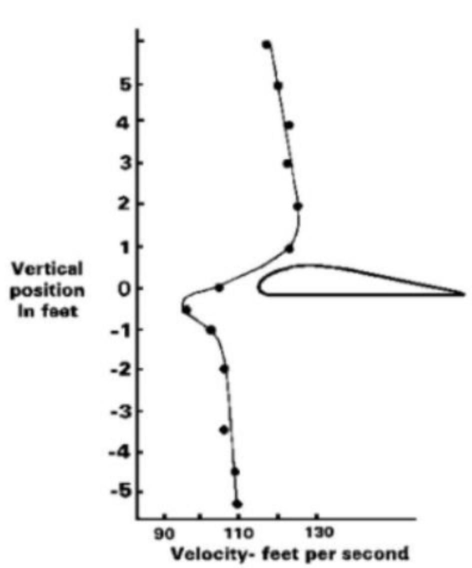
Hump theory does not allow for balsa toy gliders with flat wings, which have equal upper and lower surface path lengths. Lift is, without question, due to pressure being greater at the lower surface than at the upper surface. Thus according to Bernoulli's law, air transit time at the upper surface must be less than at the lower. This refutes the hump theory argument that upper and lower transit times must be equal. Hump theory also does not allow for inverted flight of aerobatic airplanes, which have equal upper and lower wing surface curvatures.

For mathematical test of hump theory, consider one the most popular trainers, the Cessna 150 or 152, which has wings of 160 square feet total area, upper surface path about 1.6 percent longer

than the lower, and can fly, flaps-up, at 55 miles per hour, or 81 feet per second. We can calculate lift according to hump theory. Let's assume near sea level air density of about .0024 slug per cubic foot, and assume no change in below-wing pressure or flow velocity, as hump theory explanations usually do. If upper surface velocity is increased by 1.6 percent in order to attain equal transit time, the change is .016 times 81, or 1.296 feet per second, making upper surface velocity 82.296 feet per second.

Now let's plug that information into the Bernoulli expression which says pressure difference is equal to one half density, times difference between initial velocity (airplane airspeed) squared and upper surface velocity squared. Pressure difference between upper and lower surfaces then is (1/2) x.0024 x [(81 squared)-(82.296 squared)]. The upper surface pressure reduction then becomes .2544 pounds per square foot. Multiplying this by wing area of 160 square feet gives total lift of 40.7 pounds, a small fraction of the 1600 pounds rated gross weight of the airplane. Minimum flaps-up flying speed for the airplane according to hump theory would be over 300 miles per hour, well above the redlined dive speed of 160 miles per hour.

If air velocity were increased because of a wing upper surface hump, it would be reasonable to expect above-wing velocity increase only directly above the wing. However, as shown in the following figures, velocity is affected even ahead of a wing.

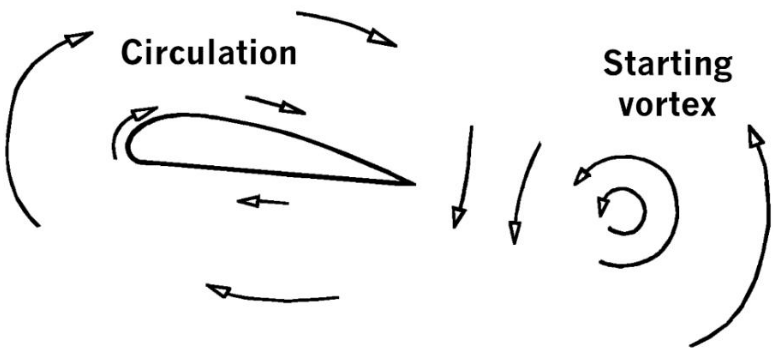


Relative velocities were measured above and below wing level in increments of one foot, and at distance one-half foot ahead of the leading edge. In the plot, the wing leading edge position represents airplane airspeed. Pitot tube airspeed plotted forward of leading edge position indicates relative velocity decrease due to forward movement of air as the wing passes. Pitot tube airspeed data greater than airplane airspeed, as plotted behind leading edge position, indicates rearward movement of air as the plane passes. Behind the plane air has followed the wing contours to depart in downward direction.

All air movement is circulatory. Ahead of the wing, air drawn toward lower above-wing pressure pressure and away from greater below-wing pressure rises ahead of the wing. In total then, upward movement ahead, rearward movement above, forward movement below and downward movement behind constitute a circulatory movement traveling with the wing, which is known as *"circulation."*superimposed on passing flow.

Aerodynamics teaching at college level, where lift calculations must correspond with the real world, disregards hump theory because it is clearly false, and instead is based on circulation theory. We can reasonably assume that many who have studied aerodynamics in college were previously taught hump theory in lower level schooling and now know it is wrong. We may justifiably wonder why some of these better educated persons have not returned to enlighten the lower levels with more appropriate teachings? Perhaps it is because higher level teaching also has questionable aspects.

Although normally presented in highly mathematical context, classical basic wing theory at the college level can be expressed in simple terms without math. According to classical theory, a wing begins to produce lift when a "starting vortex" is left behind as the wing moves forward. This vortex is said to, by a somewhat vague process, cause "circulation" to appear around the wing.



With circulation superimposed on passing flow so that upper surface air flow velocity is greater than that below, lift can be explained, as in hump theory, in connection with Bernoulli's law. *A flaw in this explanation is that physical principles explaining how the starting vortex causes wing circulation is a bit hazy.* Other invocations of induction without sound physical reasoning produce classical terms of "induced downwash," "induced angle of attack," and "induced drag." This classical explanation is a sort of mathematical analogue, adopted from electromagnetic theory. It doesn't really explain the physics, but is nevertheless quite useful in that the equations from electromagnetism produce results corresponding to the real world of wing operation.

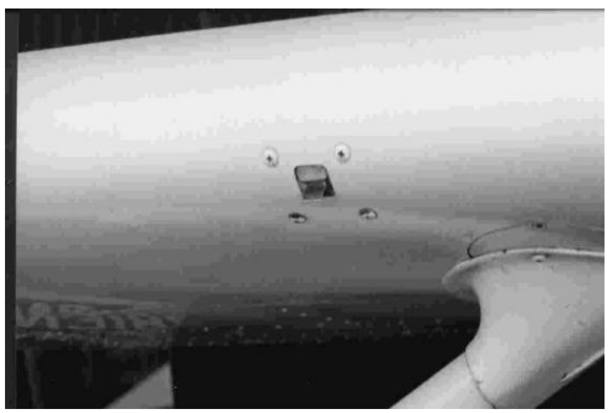
Unfortunately, or fortunately, depending on point of view, hump theory provides a "plausible" explanation of lift for the non-mathematical student, while the mathematics of electromagnetic theory and electromagnetism, from which induction concepts arise, adapts well in wing performance calculations. Thus flight instructors have an explanation for flying students, aerodynamicists and engineers find little reason to question the physics of calculations which seem to work, and physicists interested in more exotic research may have little interest in mundane mechanics of popular aerodynamics, where the starting vortex does indeed develop, and simultaneously above-wing flow develops greater velocity. These phenomena, however, are easily accounted for without invoking theinduction effects of electromagnetism.

Aerodynamic lift of a wing can be explained and calculated through simple application of Newtonian physics. Air flow following the contours of a wing in normal flight departs in a downward direction. In this redirection of flow, downward momentum is produced. Upward reaction force (or lift) must be equal, according to Newtonian physics, to the downward rate of change of air momentum. Inclination of a wing lower wing surface deflects some air downward there, while greater downward deflection is produced as flow follows the downwardly-curving

upper surface. In the downwardly-curving flow, an upward pressure gradient exists which opposes atmospheric pressure to cause upper surface pressure reduction. Bernoulli's law is satisfied with velocity changes related to pressure changes when oncoming air accelerates over the wing leading edge into the reduced pressure above the wing and decelerates in encounter with increased pressure below the leading edge. The pressure difference also accelerates air upward around the leading edge. These accelerations occur in accordance with Bernoulli's law, but the greater upper surface velocity is more easily explained as *resulting* from pressure difference, rather than causing it as popular theories teach.

As air is accelerated downward by wing passage, upward *recirculation* occurs all around the airplane, away from higher pressure below and toward lower pressure above. Thus recirculation occurs forward and upward around the wing, and laterally outward,upward and inward to produce twin *trailing vortices* which is made visible in smoke behind aerobatic plane wings at airshows.

Forward recirculation carries upwash into which the wing flies. Near stall condition, upwash velocity rounding a wing leading edge can be greater than the forward velocity of the airplane, pushing a stall warning switch tab, as shown here on a Cessna 182, forward and upward to operate a stall warning horn.



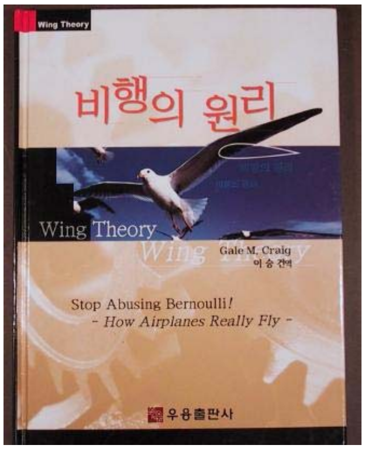
Energy is recovered from leading edge upwash as circulation rounds the leading edge to produce centrifugal pressure reduction, known as "leading edge suction," and forward thrust. Leading edge suction is sometimes used to operate a stall warning horn, as on this Cessna 175.

Leading edge pressure reduction produces forward thrust on the wing, but curvature of circulation around the rear produces opposing rearward thrust. If these were equal they would

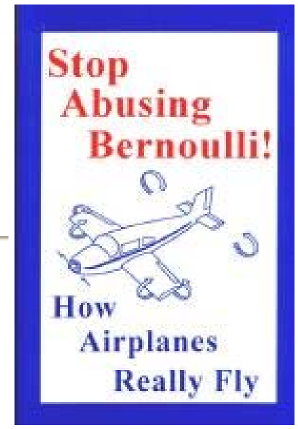
cancel, but energy lost into lateral recirculation around the wing ends causes forward thrust to be less than rearward thrust. The difference between these thrusts appears as drag, commonly referred to as "induced drag," because the classical mathematics treatment is similar to that of electromagnetism and electromagnetic induction.

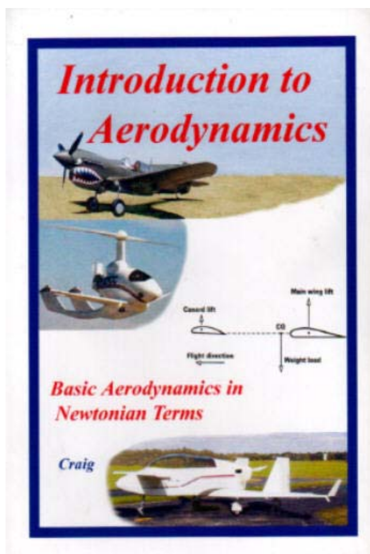
>

Much more of the story of downwash and recirculation, and how they relate to design and performance of wings and airplane configurations, is presented in a 1999 book on the subject, recommended by Peter Garrison in the July 1999 issue of *FLYING MAGAZINE*, with 160 pages and over 100 illustrations, titled *"Stop Abusing Bernoulli!-- How Airplanes Really Fly,"* ISBN 0-9646806-2-9.



Advertised in Sport Aviation Magazine, the book has sold to many countries of the world and has been translated into Korean for use in Pusan National University.





A second book with more detailed presentation, published in 2003, titled *Introduction to Aerodynamics* ISBN 09646806-3-7, is in hardcover with 224 pages and 167 illustrations. Books can be ordered from your local book store, and are in stock for immediate delivery from Academy of Model Aeronautics museum book store in Muncie, Indiana, phone 765-289-4236. Sample pages can be found on Amazon.com by clicking here.

Author Gale Craig, retired from General Motors Research and Development, holds a Master's degree in physics and is named as sole inventor in sixteen US patents in widely varying areas. He is a pilot of 1600+ hours and owns a Cessna 182.

More information on lift with circulation, can be found by clicking on the Regenerative Press link. Or just type regenpress.com into your browser.

Comments or questions? galemcraig@aol.com

THE AUSTRALIAN

Print this page

Flying feat a jumbo step for the human race

Geoffrey Thomas
18nov05

IT was a night and a day, and another night and yet another day, to remember.

As we settled into our seats on the 777-200LR in Hong Kong, some wag quipped: "Are we there yet?"

We all laughed but in fact we didn't want to arrive just yet. We were taking part in history.

Helping the 35 passengers and crew to create history was a fuel load of 164 tonnes, and in our sights were two Qantas records.

Qantas set a distance record of 17,982km in 1989 when its first 747-400 flew non-stop from London to Sydney on its delivery flight.

That flight had only 18 passengers and crew, no galley equipment, used special high density fuel and the 747 was towed to the runway to save fuel. It took 20 hours and nine minutes and the aircraft used up most of its 183.5 tonnes of fuel.

The other record was "The Order of the Double Sunrise", which wartime passengers received on the 27-33 hour non-stop flight from Koggala Lake in southern Ceylon to Perth in a Qantas twin-engine Catalina flying boat.

Those Catalinas were stripped down and had no guns -- or electric hot plates for making coffee -- and they could only carry three passengers.

No such austere flying conditions for us. Boeing had fitted out its 777-200LR demonstrator with a luxury interior but every effort was made to conserve fuel and the aircraft was specially washed down to rid it of 150kg of dirt. Passengers were restricted to just 18kg of baggage including laptops and cameras. The 777-200LR was pushed back from the stand at 10.08pm and towed to the end of the short taxiway to save fuel. At 10.22pm, the engines were started and we were under way four minutes later. Pilot-in-command, Captain Suzanna Darcy-Hennemann, pushed the throttles all the way forward at 10.30pm and within 40 seconds we were airborne to rousing cheers.

The aircraft took off at 711,000lb, well under its maximum take-off weight of 766,000lb.

Setting a world record is not as simple as just flying from one place to another. On board was Arthur Greenfield from the National Aeronautic Association to certify that Boeing followed the complex rules to the letter.

The NAA has plenty of experience in such things, having monitored the Wright Brothers' distance-record flight in 1905 - and every record flight since.

Under the NAA rules, Boeing selected three "waypoints" three hours before takeoff.

Our first marker was on the International Dateline north of Midway Island. The second was over Los Angeles International Airport and the third over New York's John F. Kennedy International Airport.

At the first, NAA's Greenfield sat with the pilots to witness the aircraft's flight displays confirm that we had indeed passed over the waypoint. The pilots then turned the 777 northeast to find a promised jet stream that would give us a kick. It did. A 244km/h tailwind had us at 1137km/h and speeding towards Los Angeles.

Then we were soon over Denver to pick up more fair winds, and turned east towards New York, which slipped under us at 07.06 Co-ordinated Universal Time.

Newfoundland was next and the first hint of our second sunrise had BBC and CNN in the cockpit. As the Order of the Double Sunrise record fell, Captain Rod Scarr announced that Qantas's long-standing distance record had also just fallen.

When the 777-200LR touched down in London a few hours later, it had flown 22,520km. But Boeing could only claim 21,601km, as the shortest distance between the waypoints.

Geoffrey Thomas was a guest on board the 777-200LR

Compiled by Kevin Bishop
Frasers Aerospace

FRASERS
AEROSPACE