Part I

Fixed-Wing Aircraft Performance
Chapter 1
Introduction

... but the fact remains that a couple of bicycle mechanics from Dayton, Ohio, had designed, constructed, and flown for the first time ever a practical airplane.

J. Dos Passos, in “The Big Money”, 1932

After an uncertain start at the beginning of the 20th century, aviation has grown to a size on a global scale. By the year 2000, over 100 million passengers traveled through the airports of large metropolitan areas, such as London and Chicago. In the same year, there have been 35.14 million commercial departures worldwide, for a total of 18.14 million flight hours\(^1\). Demand for commercial air travel has grown by an estimated 9% a year since the 1960s. The expansion of the aviation services is set to increase strongly. Today, every million passengers contribute about 3,000 jobs (directly and indirectly) to the economy. Therefore, aircraft performance is a substantial subject.

The calculation and optimization of aircraft performance are required to:

- Design a new aircraft;
- Verify that the aircraft achieves its design targets;
- Efficiently operate an existing aircraft or fleet;
- Select a new aircraft;
- Modify, upgrade and extend the flight envelope;
- Upgrade and extend the mission profile;
- Investigate the causes of aircraft accidents;
- Provide data for the aircraft certification (Certificate of Airworthiness).

The engineering methods for the evaluation of aircraft performance are based on theoretical analysis and flight testing. The latter method is made possible by accurate measurement techniques, including navigation instruments. Flight testing is essentially an experimental discipline – albeit an expensive one. Performance flight testing involves the calibration of instruments and static tests on the ground, testing at all the important conditions, gathering of data from computers, data analysis, and calibration with simulation models. Wind tunnel testing is only used for the prediction of the aerodynamic characteristics. Graphical methods, such as finding the intersection between two performance curves, belong to past engineering practice. Analytical and numerical methods, including the equations of motion of the aircraft, are the subject of this textbook. Analytical methods yield closed-form solutions to relatively simple problems. Numerical solutions address more complex problems, and allow the aircraft engineers to explore “virtually” the complete parametric space of the aircraft flight. This practice avoids expensive and risky flight testing. Methods for flight testing and evaluation of the fixed- and rotary-wing aircraft performance are discussed by Kimberlin\(^2\), Olson\(^3\) and Cooke and Fitzpatrick\(^4\), respectively.
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Due to the variety of requirements, the subject of aircraft performance intersects several other disciplines, such as aircraft design, scheduling, operational research, systems, stability and controls, navigation, air traffic operations, flight simulation, optimization, in addition to aerodynamics, structures, propulsion systems and integration. Therefore, aircraft performance is essentially a multidisciplinary subject. Among the ones well known to the aerospace engineers there is the flight mechanics approach, the dynamics and aerodynamics of flight (for example, Lan and Roskam\textsuperscript{5}, Anderson\textsuperscript{6}).

Personal interests may be involved in selecting the type of flight vehicles, as these include conventional airplanes, high-performance military aircraft, helicopters, VSTOL aircraft, rockets and vehicles for transatmospheric flight. Old and modern books on the subject deal only with some of these flight vehicles – as convenient.

The basic performance of the fixed- and rotary-wing aircraft can be calculated with little mathematical effort, using the one-degree of freedom model. However, a more accurate prediction of any performance parameter, particularly if the aircraft is maneuvering in unsteady mode, is a challenging subject, because it generally involves a number of free parameters in non-linear differential equations. It will be shown how the question of \emph{how fast can an airplane fly} is difficult to answer. In short, it depends on \emph{how it flies}.

\textbf{Performance prediction} is at the base of any concrete aircraft design methodology. The estimation of weights, range and power plant size requires the calculation of basic aircraft performance from a few input data. In this case the approximation is generally good enough for parameter estimation and design. Input from operational parameters and flight testing is required for detailed analysis.

\textbf{Performance optimization} is at the heart of design and operation of all modern aircraft. From the operational point of view, commercial aviation is driven by fuel prices, and operations at minimum fuel consumption are of great relevance. Performance optimization requires notions of optimal control theory, a subject unfamiliar to aerospace engineers.

\textbf{Performance efficiency} goes beyond the design point, and requires that the aircraft produces the best performance over the widest range of its flight envelope. For this reason, the subject of performance optimization is essential in design. The fighter jets Grumman F-14 and McDonnell-Douglas F-15 (1970s) were the first to be designed with the optimization approach, and all the aircraft of later generations were conceived in the same fashion.

In the past 30 years these optimal conditions have been increasingly challenged by environmental concerns, including noise emission, air quality near airports, global climate change and sustainability. Some aspects of the impact of aviation on climate change are the subject of routine review. Publications of relevance include the ones from the Intergovernmental Panel on Climate Change (IPCC), for example ref. \textsuperscript{7}.

1.1 PHYSICAL UNITS USED

International units (SI) are used whenever possible. Unfortunately, most data in aviation are still in imperial units. Conversion to international units is not foreseen for the immediate future. In most cases, the flight altitudes will be converted to feet, because
of the extensive practice of working out the performance parameters in term of this unit. Speeds will also be given in knots or km/h.

The SI nomenclature notwithstanding, some spurious engineering units have had to be retained in some cases. One of the most confusing units ever devised is the kg. This unit is used for both weight (force) and mass: weight in kgf is equal to mass in kgm. This equivalence can fool any experienced engineer. Unfortunately, there is no way around it, because it is more convenient to denote a weight with kgf, rather than the newton. The mass, instead of the weight, appears in the energy equations, which is the main reason for retaining the kgm. By contrast, the weight appears in the aerodynamic coefficients, and if the other parameters are in international units, then the weight must be converted into newtons. Therefore, the confusion is sometimes overwhelming.

To the student approaching the subject for the first time there is a special word of caution. It is easy to miscalculate an aircrafts performance because of the use of non-conformal units. Some of the most common errors arise from using speeds in km/h instead of m/s, and kN or kW instead of N and W (thrust and power, respectively). The units for specific fuel consumption can also be confusing. With some critical thinking these errors can be avoided. A range of 2,600,000 km, instead of 2,600 km, is achieved by an airplane if one oversees the coherence of units. The former result is a distance from Earth to the Moon and back three times, while the correct result is a medium range flight in many parts of the world.

1.2 PERFORMANCE PARAMETERS

A performance parameter is a quantitative indicator representing how a vehicle operates in a specific flight condition. Typical performance parameters are weights, speeds, aerodynamic loads, engine thrust and power, range and endurance, accelerations, emission indexes (noise, exhaust gases) and many more. At least 60 different parameters can be taken into account in a full aircraft performance analysis.

In accident investigation, the flight parameters considered are the air speed, the Mach number, the dynamic pressure, the altitude, the air temperature, the rate of climb or descent, the flight path angle, the side-slip angle, the angular velocities and accelerations, the load factor, the rudder position, the control surfaces position, the fuel load and the engines status.

It is not obvious what distinguishes a performance parameter from a purely aerodynamic, propulsion, operational parameter. The drag coefficient of the wing section is not a performance parameter, but the aircraft’s drag coefficient is. The wing’s aerodynamic characteristics are not a subject of aircraft performance, but the aerodynamic characteristics of the aircraft as whole are. In performance analyses the drag coefficients are the known part of the problem, while in aircraft design they are part of the problem. The thrust is by itself an engine performance; the same engine mounted and integrated on the airframe becomes an aircraft parameter. The analysis must take into account that the system engine/airframe is not the same thing as the engine alone (airframe/engine integration). The stealth capabilities of an aircraft (radar signature, thermal signature, noise emission) depend more on the design of the aircraft than its
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operation. Not all the parameters will appear on the instrument panels in the cockpit, and some of them are not relevant to the pilot.

Many performance indexes cannot simply be expressed by a single value, but are presented with charts, because they are dependent on other parameters. The combination of those parameters is essential in defining the operation of the aircraft. Typical charts are the air speed relationships, the weight/altitude/temperature charts, the flight envelopes, and the payload range.

Some performance data are readily available from the manufacturer; other data can be inferred by appropriate analysis; others are clouded by secrecy or confidentiality; and others are difficult to interpret, because the conditions under which the aircraft performs are not given. Among the most common data covered by secrecy are the drag data, the stability characteristics, the excess power diagrams and the engine performance. Other examples are the aircraft range, when the payload is not given together with the range; the altitude at which this range is achieved is not given; and the radius of action of a military interceptor – this radius, in fact, may lie in the favourite field of enemy fire.

The maximum take-off weight (MTOW) and the operating empty weight (OEW) are available for most aircraft. However, these data are not sufficient to calculate the maximum payload, because the difference between MTOW and OEW must include the mission fuel. Therefore, some educated guess is needed. A weight advantage compared to heavier rivals translates into significant revenue-earning advantages, which in a competitive market is the most important factor for choosing and operating an aircraft. It is not uncommon to find manufacturers unhappy that their performance data and charts are published in the public domain. Performance charts allow customers and competitors to look at various options, to select the most competitive aircraft and to discover the flaws of the competitors’ technology: sharing information makes everybody better players.

The purpose of this book is to take the reader through some simple performance calculations, to look at the performance data, and to give an introduction to aircraft performance optimization. A large number of data are published by Jane’s Information Systems⁸, and Flight International⁹; other valuable data for lesser known aircraft are available in Gurton¹⁰ and Loftin¹¹. The latter reference differs from the other ones because of its critical analysis. Loftin, in his extensive bibliography, also points to additional sources of aircraft performance data. Further data have been taken from official documents of the international authorities (FAA, ICAO), and specialized publications such as AGARD¹², ESDU, and by our own research¹³. ESDU (Engineering Sheets Data Units) provide data and methods on all areas of performance, and are of invaluable value to the practitioner engineer. Of particular interest are landing¹⁴ and take-off performance¹⁵, drag of airframes¹⁶, and engines range and endurance¹⁷.

Updated data that are not proprietary are published regularly by the magazines Flight International and Flug Revue. All flight manuals report the essential performance curves of the aircraft and its engines, and include data that may not be available elsewhere. Most flight manuals are now available in electronic form, and represent a great wealth of information for the aircraft performance engineer.

As in any other technology sector, the operator of an aircraft is concerned that the performance parameters quoted by the manufacturer match the actual performance, therefore accuracy of performance prediction methods is essential.
1.3 PERFORMANCE OPTIMIZATION

In the early 1950s, computers made their first appearance in aerospace engineering. Bairstow wrote in 1951 that:

The use of electric calculators is coming in to reduce manual labor, but there is little hope of doing nearly all that we would like to do.

Computer solutions of aircraft performance are now routine jobs, and have reached a phenomenal level of sophistication, to include the coupling between flight mechanics, aerodynamics, structural dynamics, flight system control and differential game theory. With analog computers first, then with digital computers, the problems solved grew in complexity. See, for example, the 1959 edition of Etkin’s book on flight dynamics to gain a perspective. In 1982, Ashley exemplified the problems of optimization in a paper titled “On Making Things the Best”. The author argued, among other things, that flight planning ceased to be a matter of hand calculation by the time commercial jet propulsion was introduced (late 1950s).

There are two categories of optimization: Optimization of aircraft performance during the design phase, and optimization of operational performance for the given airplane. In the former case, one can investigate the alternative changes in configuration that improve one or more performance parameters. This is more appropriately the subject of aircraft design. We will consider some cases of operational optimization. An excellent source for optimization problems with aircraft applications is the classic book of Bryson and Ho on optimal control. Some of these problems, including multistage rocket trajectories, were also reviewed by Ashley.

Today there are programs that plan optimal trajectory routes to minimize DOC (Direct Operating Costs), while complying with several airline constraints. These programs have several types of input data: weather conditions, route, aerodynamics, aircraft performance, and flight-specific information, such as payload, fuel cost, etc. On output they provide the amount of fuel for optimal cruise altitude, climb and descent points, optimal cruise speed, and flight path.

1.4 CERTIFICATE OF AIRWORTHINESS

The Certificate of Airworthiness is a document that grants authorization to operate an aircraft. It specifies the limits of operation of the vehicle in terms of weights, take-off and landing requirements, and a number of other parameters, such as maintenance records, service history and compliance with safety regulations.

The certificate proves that the aircraft conforms to the type specified and it is safe to fly. The certificate is valid as long as the aircraft meets the type specification (commercial, commuter, utility, etc.), it is operated safely and all the airworthiness directives are met. The aircraft may lose its certificate for a number of reasons, including modifications, upgrades, and new directives approved by the international organizations that make the aircraft obsolete, not just unsafe to operate. Other documents are generally required, such as the type certificate data sheet, the certificate of maintenance, and a list of other papers. These documents seldom contain detailed performance data.

Certificates of Airworthiness are issued by the Federal Aviation Administration (FAA) in the USA, by the European Aviation Safety Agency (EASA), by the Civil
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Aviation Authority (CAA) in the UK and by other national and international bodies around the world. Certification is a complex legal and technical matter that is beyond the scope of this book.

1.5 UPGRADING OF AIRCRAFT PERFORMANCE

The age of bicycle mechanics has long passed. In the current technology situation, most aircraft are likely to be upgraded and modified to fit the changing market and technological advances. The technology that is fitted over the years can be phenomenally different from the first design. The service time of a single aircraft is of the order of 20 to 25 years, and the life of an aircraft family may exceed 50 years. A lifetime career can be devoted to a single airplane. The famed aircraft engineer Reginald J. Mitchell designed 24 aircraft, including the Spitfire, before dying prematurely, aged 42, in 1937.

To be fair, in the early days of aviation, a new aircraft could roll out of the factory in a few months. Indeed, some aircraft were prototypes that logged a few flights and then were scrapped – if they survived a crash. Figure 1.1 shows the Avro Model F (1912) at Manchester. This airplane was the first to have an enclosed cockpit, but it was capable of flying at only one speed, 65 mph. Only two airplanes were built. The picture to the right shows the airplane after it crash-landed in May 1912 due to an engine failure. The photo appears to have been published as a postcard.

It took only 43 days to build the Ryan NYP that made the transatlantic crossing in 1927, for a total of 850 engineering hours (including performance and flight testing) and 3,000 man-hours for construction. In 1936, it took just one year for the German aircraft designer Kurt Tank from concept to first flight of the Focke Wulf Condor Fw-200, the first long-range passenger (and later reconnaissance and bomber) aircraft to fly from Berlin to New York without en-route stop (1938).

The wings of the Douglas DC-3 (1935), one of the most successful aircraft ever built, had simple performance improvement devices, a split flap for landing and outer-board ailerons for roll control. A jet aircraft of the first generation, such as the

![Figure 1.1](image-url)  
*Figure 1.1  The Avro-F, built by A.V. Roe (1912). (a) Photo first published by the magazine Flight on 18 June 1942; (b) photo from the AV Roe Archives. Family outing with airplane crash (25 May 1912).*
Boeing 727 (1958), had four outer-board leading-edge slats, three inboard leading-edge Kruger flaps, two banks of triple-slotted trailing-edge flaps, an inboard aileron for high-speed roll control, an outer-board aileron for low-speed flight, and seven spoilers (including five flight spoilers and two ground spoilers), also used as air brakes. This airplane is still flying.

By the 1960s, commercial airplane design and testing required thousands of man-years. The Boeing B-747-100, which first flew in 1969\textsuperscript{24,25}, required 15,000 hours of wind tunnel testing, 1,500 hours of flight testing with five aircraft over a period of 10 months, and 75,000 technical drawings\textsuperscript{1}. The latest version of this aircraft consists of about 6 million parts, 274 km of wiring and 8 km of tubing!

The B-747-400 incorporates major aerodynamic improvements, including a more slender wing with winglets to reduce drag. A weight saving of approximately 2,270 kg was achieved in the wing by using new aluminum alloys. Finally, the version B-747-400ER has an increased take-off weight of 412,770 kg. This allows operators to fly about 410 nautical miles (760 km) further, or carry an additional 6,800 kg payload, for a range up to 14,200 km.

An even older airplane is the Lockheed Hercules C-130A. Its first model was delivered to the US military in 1956. The design of this aircraft actually started several years earlier. By the early 1960s, a VSTOL variant was designed\textsuperscript{26}. Since then, the aircraft has progressed through at least 60 different variants. The current C-130J is actually a new airplane. Compared to the earlier popular version C-130E, the maximum speed is increased by 21%, climb time is reduced by 50%, the cruising altitude is 40% higher, the range is 40% longer, and its Rolls-Royce AE-2100DE engines generate 29% more thrust, while increasing fuel efficiency by 15%. With new engines and new propellers, the C130-J can climb to 9,100 m (28,000 feet) in 14 minutes.

Another example is the military utility helicopter CH-47, which has been in service since 1958. The basic performance upgrades for this aircraft (versions A to D) are reported in Table A.19 on page 506. In particular, the MTOW has increased by over 50% and the useful payload has doubled. To the non-expert the aircraft looks the same as it did in the 1960s.

Technological advances in aerodynamics, engines and structures can be applied to existing aircraft to improve their performance. Over time weights grow, power plants become more efficient and are replaced, aerodynamics is improved by optimization, fuselages are stretched to accommodate more payload, and additional fuel tanks are added. This is one of the main reasons why aircraft manufacturers are not challenged to start a brand new design.

The conversion of aircraft for different commercial or military applications, and the development of derivative aircraft from successful aircraft require new performance calculations, and a new certification. For example, the KC-10 tanker aircraft was derived from the commercial jet DC-10 (commercial to military conversion), and the Hercules C-130 was converted to the Lockheed L-100 (military to commercial). The conversion practice is more common with helicopters.

### 1.6 MISSION PROFILES

A mission profile is a scenario that is required to establish the weight, fuel, payload, range, speed, flight altitude, loiter and any other operations that the aircraft must be
able to accomplish. The mission requirements are evidently specific to the type of aircraft. For high-performance aircraft they get fairly complicated, and require some statistical forecasting.

Over the years many commercial aircraft operators have specialised in niche markets, which offer prices and services to selected customers. These niches include the executive jet operators between major business centers, operators flying to particular destinations (oil and gas fields), the all-inclusive tour operators to sunny holiday resorts, the no-frills airlines flying to minor and underused airports. These operators have different schedules and cost structures.

First, let us start with long range passenger operations, which are serviced for the greatest part by subsonic commercial jets. The basic principle is that the airplane takes off from airport A and flies to airport B along a recognized flight corridor, then returns to A. The main parameters of the mission planning are the distance between the airports, the flight time, the downtime at the airport for getting the airplane ready (also called time-on-station), the flight speed, the local air traffic, and the departure times at both ends. Back at the airport of origin, the day is not over for the aircraft, and the operator wishes to utilize the airplane for another flight to the same destination, or to another destination – if possible. The key is the departure time, and the minimization of the curfew. Figure 1.2 shows the typical scheduling profile of such an airplane over a transatlantic route from a major airport in Europe to an airport on the East Coast of the United States.

Due to the time-zone effect, a late morning departure from Europe arrives to the USA in the mid-afternoon. An early evening departure arrives back in Europe in the early hours of the day after. Over the 24-hour period the airplane will have done a return flight and worked about 14 to 16 hours. For a flight arriving late in the evening, a return may not be possible until early morning on the next day. This adds to the operational costs, because of the need of maintaining the crew away from the home port. The time needed to get the aircraft ready for the next intercontinental flight may require up to 3 hours. Boarding of the Boeing-747 requires 50 to 60 minutes.

**Figure 1.2** Scheduling of transatlantic flight. The numbers on the left and right side are local times.
Scheduling of the type shown in Figure 1.2 leads to a block time of the order of 700 to 900 hours per year (depending on aircraft and service route). An airplane flying a day-time shorter route, and returning in the mid-afternoon, should be able to make another return flight, to the same destination or otherwise. For an airline company operating anything above a dozen airplanes, scheduling and optimal operation of the fleet is a complex problem. Events such as bad weather can lead to dozens of airplanes and flights crew out of position for several days. Scheduling and operation of aircraft is a subject for operations research, and is addressed by specialized publications. Gang Yu is a good compendium to start with\textsuperscript{27}. It deals with demand forecasting, network design, route planning; airline schedule planning, irregular operations, integrated scheduling, airport traffic simulation and control, and more.

1.6.1 Fighter Aircraft Requirements

The fighter aircraft has evolved from a reconnaissance airplane of the First World War to the most complex aircraft of modern days. Von Kármán\textsuperscript{28} reported that fighter aircraft first flew over the battlefields of Europe to spy on enemy lines. Obviously, enemy aircraft wanted to prevent this happening, so their pilots started shooting at enemy aircraft with a pistol. This was the beginning of a dog fight. Toward the end of the war, the Dutchman Anton Fokker, working at the service of the German Army, invented a system that synchronized the shooting of a machine gun through the propeller (interrupter gear) – mounted on a single-seater monoplane. With the interrupter pilots had their hands free to maneuver and fight at the same time. This was heralded as the birth of the fighter aircraft (see Stevens\textsuperscript{29} and Weyl\textsuperscript{30} for historical details).

The requirements for fighter aircraft now include multipurpose missions, aircraft with complex flight envelopes, several configurations (changeable in flight), supersonic flight, combat capabilities, delivery of a wide range of weapon systems (night and day), and maneuverability. There are dozens of different mission scenarios, as discussed extensively by Gallagher \textit{et al.}\textsuperscript{31} Typical missions are: basic, assault, combat, retrieval, close support, transport, refuel, and reconnaissance. For each of these missions there is a specific take-off weight, mission fuel, payload, range, maximum rate of climb, and service ceiling. This field is now so advanced that engineers use differential game theory and artificial intelligence to study the effectiveness of a given aircraft, and the tactical maneuverability to incoming threats (see, for example, Isaacs\textsuperscript{32} for some problems on this subject).

One example of mission profile for this type of aircraft is shown in Figure 1.3. Such a profile must include warm-up, acceleration, take-off, climb, cruise, dash, combat, decelerate/climb, descent, and landing (with allowance for loiter and fuel reserve). In a more detailed breakdown, a typical plan may look like that in Table 1.1. The analysis of the various flight sections is essential in predicting the mission fuel; the mission fuel is essential for returning to base.

An alternative graphic method for indicating a mission profile is shown in Figure 1.4, which represents an interdiction operation. The numbers indicate each flight segment. The vertical axis is an arbitrary flight altitude. The graph shows the mission radius (in arbitrary scale) and the point of engagement. Each segment is further specified by requirements such as those on Table 1.1.
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Figure 1.3  Generic mission profile for fighter aircraft.

Table 1.1  Summary of flight segments of a supersonic jet fighter.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-up, acceleration, take-off</td>
<td>2 minutes; 0.5 minutes at maximum power</td>
</tr>
<tr>
<td>Climb</td>
<td>at maximum power</td>
</tr>
<tr>
<td>Dash speed</td>
<td>$M = 1.8$, at 12,000 m (39,370 ft)</td>
</tr>
<tr>
<td>Combat</td>
<td>2 minutes, maximum power, dash speed</td>
</tr>
<tr>
<td>Subsonic cruise</td>
<td>30 minutes, $M = 0.85$</td>
</tr>
<tr>
<td>Decelerate and climb</td>
<td>to $M = 0.8$, at 9,500 m (31,168 ft)</td>
</tr>
<tr>
<td>Descent and landing</td>
<td>to sea level; no fuel credit</td>
</tr>
<tr>
<td>Loiter</td>
<td>10 minutes at sea level, minimum fuel</td>
</tr>
<tr>
<td>Landing</td>
<td>45 s at minimum power</td>
</tr>
<tr>
<td>Reserve fuel</td>
<td>5% of total mission fuel</td>
</tr>
</tbody>
</table>

Figure 1.4  Generic mission profile for interdiction operation.
The *dash speed* is a supersonic speed that the aircraft can maintain for a limited amount of time, or flight distance. It is usually the maximum speed at the best flight altitude. As indicated in the table, this altitude is around 12,000 m (39,370 feet).

*Loiter* is the operation around an airport. It usually consists of various turns along prescribed flight corridors, before the aircraft is permitted to land. Delay in landing (and longer loiter) may be due to air traffic control and weather conditions.

A performance index characteristic only of fighter jet aircraft is the *effectiveness*. Effectiveness is defined as the product of ordnance transport rate, availability in war time and kill effectiveness. The ordnance transport weight is the product of the ordnance mass and the number of sorties per day. The availability in war time is the time the aircraft is available for operations (compared to downtime for maintenance, service, loading, etc.). The killing effectiveness is the knocking-out success rate.

### 1.6.2 Supersonic Commercial Aircraft Requirements

After the Concorde era came to a close, no serious attempts have been done to replace the aircraft and operate a commercial flight at supersonic speeds. Nevertheless, the theoretical analyses regarding the feasibility of such an airplane under modern environmental and financial constraints abound. A new generation of supersonic civil transport aircraft that would replace the Concorde, should be able to fly longer routes, possibly at higher speeds. A Los Angeles to Tokyo route would require a cruise speed of \( M = 2.4 \) in order to be able to schedule two round trips over a 24-hour period. A replacement for Concorde, operating on the North Atlantic routes, should be able to fly at \( M = 2.0 \), or possibly lower, if the turn-around time can be reduced. This speed is important in the cycle because it allows the airplane to be serviced at both ends and to avoid long curfews. The operators of Concorde could make a profit (once the mortgage for the acquisition of the aircraft was taken out of the spreadsheets) by having two return flights per day.

### PROBLEMS

1. Discuss the possible mission profiles for a VSTOL aircraft, and extract a set of performance criteria that can be applied to all operational conditions.
2. Make a list of all the performance segments of a supersonic jet fighter, and provide a critical discussion. Provide a scenario to deal with a fuel shortage at the end of a scheduled operation, before returning to base.
3. You are asked to plan a flight time table between London and Berlin. Provide a plan for a subsonic jet transport that maximizes the block time for the operation between the two cities. Analyze the alternative, consisting in operating a turboprop aircraft. Do the necessary research of the data needed for the solution of this problem (flight corridor, distance in nautical miles, estimated flight time, flight speeds, etc.).
4. The Boeing B-52 is one of the oldest aircraft still in service. It has progressed from the first version in 1954, B-52A, to the version B-52G. Do the necessary research to investigate how propulsion, aerodynamics and general performance
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parameters have changed from the first to the latest version. List the most important quantities in a spreadsheet, and draw a conclusion.

5. Analyze the ground operations required to get a Boeing B-747-400 ready for an intercontinental flight (refueling, systems checks, food supplies, water, boarding of passengers). Produce a spreadsheet that indicates the time of each operation, and which operations can be performed in parallel. (Problem-based learning: additional research is required).