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Rationalizing Aircraft Performance Dynamic Modeling in Airline Fleet Planning Decisions

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Abstract

This study develops a dynamic model and identifies factors that can be used to evaluate aircraft performance. Aircraft performance modeling is a cornerstone ingredient in airline fleet planning decisions. Fleet planning is a core aspect of airline operational efficiency. The wrong aircraft in the wrong mission can cost an airline both operationally as well as financially. The study focuses on the evaluation of modern commercial jet aircraft larger than 50 seats used by airlines. Development of an acceptable model would assist airlines in decision making when procuring aircraft for the airline specific requirements. Fleet flexibility is also an important criterion today and the tool would also assist in matching the right aircraft to the optimum flight schedules. Currently, different aircraft types are compared by their static parameters, such as payload range, wingspan, gross weight, engine s.l.s.t. (sea-level static thrust), aircraft manufacturer, and even manufacturer of engine. However, these are inadequate measurements of aircraft performance as they consider static parameters alone. Two airplanes that look exactly the same may have different power engine thrusts and certified gross weights. Either of these two parameters cause to perform differently. Mismatching aircraft types to their intended missions will occur if, during the procurement study phase, the airline does not consider future and potential variations in its route structure. A list of aircraft "static" features hence is insufficient as an evaluation tool. We propose a definite distinction between *static* and *dynamic* parameters and as such we believe we contribute to the academic literature through the consideration and analysis of these different parameters. While static parameters as mentioned before are well known and used, dynamic parameters are less common, and perhaps less understood by higher-level management. Because dynamic parameters by definition have variable values, cause and effect between these parameters become an interesting phenomenon to be also investigated. In the paper, after reviewing the definition of "aircraft performance" and its impact on airline operations, we provide a multidimensional performance model for assessment of aircraft.

Keywords: Aircraft design and airline fleet planning; Airline strategy, Management and operations; Airline and airport performance.

1. Introduction

This study develops a model and identifies factors that can be used to evaluate aircraft performance. The focus is on the evaluation of modern commercial jet aircraft (50 passenger seating capacity and larger) commonly used by airlines. Development of a good and applicable model would assist airlines in decision making when procuring aircraft for specific airline requirements vis-à-vis operational deployment. Fleet flexibility is also an important criterion today and the tool would also assist in matching the right aircraft to the optimum flight schedules.

Currently, different aircraft types are compared by their static parameters, such as payload range, wingspan, gross weight, engine s.l.s.t. (sea-level static thrust), aircraft manufacturer, and even manufacturer of engine. However, these are not comprehensive measurements of aircraft performance. Two airplanes that look exactly the same may have different power engine thrusts and certified gross weights. Either of these two parameters can mean that aircraft perform differently. Operating weights, thrust, and payload-range are characteristics that have variable values in actual operating conditions. Table 1 provides a basic side-by-side comparison of two aircraft in regard to static parameters.

Criteria	Aircraft A	Aircraft B
Weight W (lb)	23,500	24,000
Wing area S (ft2)	308.26	380.0
Wing Span b (ft)	44.79	50.43
Thrust T (lb)	7,400	7,400
OEW (lb)	12,700	14,154
Maximum Payload:		
No. of Passengers	10 (2,000 lb)	8 (1,600 lb)
Baggage (lb)	1,050	545
Maximum fuel W_f (lb)	9,464	8,708
Stall speed V_s (mph)		
(full flaps and gear down)	114	104
Service Ceiling h_c (ft)	45,000	45,000

Table 1. Example comparison between two twin-engine aircraft (Hale, 1984)

Mismatching aircraft types to their intended missions will occur if, during the procurement study phase, the airline does not consider future and potential variations in its route structure. In other words, medium to long turn planning and interdepartmental coordination are essential ingredients of the aircraft decision-making model. If an aircraft is selected based on attractive commercial terms for use between airports that have long runways, it might not perform so well if the network changes to airports with shorter runways and the aircraft cannot carry as much payload due to runway take-off weight restrictions.

Mismatching can also occur when an airline expands its fleet rapidly from available aircraft on the second hand or unused aircraft market. The over-riding factor then tends to be to procure similar model aircraft to the existing fleet at the best commercial terms despite differences in performance-impacting features such as engines or certified operating weights. Getting another "Boeing 767", even with the same engines may not fit if the new addition has lower thrust rated engines and cannot meet the same mission requirements as the existing fleet. These seemingly minor details can affect an airline's bottom line significantly. Restricting certain aircraft for use on certain routes could help mitigate this problem, but it then consumes valuable management time and reduces scheduling flexibility.

A list of aircraft "static" features hence is insufficient as an evaluation tool. The argument this study advances is that there is a definite and clear distinction between *static* and *dynamic* parameters. While static parameters as above-mentioned are well known and used, dynamic parameters are less common, and perhaps less understood by higher-level management. Because dynamic parameters by definition have variable values, cause and effect between these parameters become an interesting phenomenon to be also investigated.

For example, short runway take-off limiting weight can be a valuable dynamic measurement. But it would be essential to know if this limitation is affected more by the wing aerodynamics or the thrust of the engine. If the latter is more important, then in an exercise to procure similar (of the same wing design) aircrafts we know that we should look more closely at the engine thrust specifications.

In the section that follows, after reviewing the definition of "aircraft performance" and its impact on airline operations, we suggest a multidimensional performance model for aircraft assessment.

2. Aircraft Performance

Clark (2001) defines the purpose of the study of performance in the context of commercial aircraft, as the optimization of "the payload and range abilities of an aircraft according to a set of physical and ambient limitations." He goes on to say that "the physical limitations concern the configuration of the aircraft and the characteristics of the runways from which it takes off and lands. The ambient limitations concern operational elements such as temperature, wind and airfield elevation."

A cruise speed criterion can be added to the above. In comparing two aircraft types, *ceteris* *paribus*, the aircraft that achieves the same payload range capability in a shorter time would obviously have a commercial advantage for the same capital investment.

Matching the aircraft to its designated mission also helps to define the expectation of the operator. An aircraft that is designed for short-range operations obviously would not be suitable for long range and would either cost more in fuel or suffer reductions in payload. Similarly, an aircraft designed for large passenger capacity would not be economical to operate on a mission that had low passenger demand. Therefore, it is important not to describe an aircraft as “good” or “bad” in an absolute sense, but only in relation to the intended mission. However, defining such intended missions confidently is a problem that has several variations particularly in the current fast changing airline environment. Grover (1990) mentions “Let us assume the existing route network is known and defined” in the evaluation of aircraft, and proceeds to show selection of the aircraft that performs best overall on the network, based on commercial decisions and payload-range. Events that can produce significant disruptions to the industry (ex. catastrophic events or economic slowdowns) can throw totally unexpected curves to well-planned schedules. Consequently, the whole fleet procured for a certain diminishing market may be reallocated to another completely different market in an attempt to recover revenues from new sources. Different markets mean different airport operating conditions and different types of missions.

Furthermore, the high asset value and costs of introducing a fleet type into an airline are disincentives for changing the fleet type quickly. Re-training of flight crew, maintenance crew, spares inventories, even customized ground equipment are all complex issues that cannot be changed overnight. In practice an aircraft type can see service of up to 10-20 years in an airline, well beyond a 5-year financial plan.

Hence the problem is to define missions that may be beyond the current ones that are operated or envisaged. It could thus be argued that an aircraft type that demonstrates the highest operational flexibility compared to other aircraft in its class would be more suitable than a type that may be slightly cheaper to buy but offers less flexibility in operation.

2.1. Operational Flexibility

We outline and use a "typical" airline market as a backdrop in the type of flexibility desired to test our assumptions. In a "typical" airline operational environment, routes can exhibit extreme differences in short and long runway airports, as well as very short and long distance requirements. Large and highly populated cities tend to have large airports and runways while sparsely populated cities usually have smaller airports and corresponding runways. "Transports used for travel between and from smaller cities cannot count on finding 10,000-ft runways." (Hale, 1984)

Ironically the distant small communities can be the ones that need air links the greatest as there will be fewer alternatives such as railroads or automobile highways or, in cases of island nations, limited transportation option by sea. Therefore, an operator can be faced with such a contradictive long-range mission, requiring a small capacity aircraft, a large fuel capacity, but with the aircraft restricted in payload due to the short runway at the community.

Let us consider the two aircraft performance factors that directly affect this operational flexibility: Payload-Range and Speed.

2.2. Payload-Range

Payload is the sum of revenue-earning passengers and cargo capacity. It is usually measured by weight and the maximum payload is the weight difference between the maximum allowable take off weight and the aircraft operating empty weight including fuel. It is limited by structural constraints (Maximum Zero Fuel Weight). The main objective is to transfer passengers or cargo from point A to point B. "The ton-km and the passenger-km are the basic products an airline is selling" (Wagenmakers, 1991). In this study we will not distinguish between passengers and cargo since aircraft can be configured to carry a mixture of both or either exclusively depending on the operator's core business focus.

Range defined as the distance "from A to B" is as critical as the payload quantity. It is a parameter that distinguishes preference for air travel over other forms of transportation, land or sea. Given that range is determined by fuel capacity and fuel burn rate, an aircraft designed for short range may have small fuel tanks and large payload capacity, versus a long-range aircraft that has large fuel tanks and lesser payload capacity.

An ideal aircraft would have great range capability but incur little payload penalty for short-range missions. The ability to trade payload for fuel is hence a criterion. Aircraft may have Maximum Zero Fuel Weight (Maximum weight of the aircraft including payload without fuel) but structural limits that do not permit a long-range aircraft to trade range (fuel) for payload.

Typically larger aircraft fly further. Some aircrafts that buck this trend are variants of airplanes like the Boeing 767 or Airbus A330 that are designed to fly long-range missions with a medium sized payload.

Figure 1, portrays a typical payload-range chart with fuel limitations. Of the four factors take-off performance, fuel efficiency, power, aerodynamics, we see that payload-range is a function of Take-Off Performance (MTOW or Maximum Take-Off Weight allowed) and Fuel Efficiency. In Zone A, the decision whether the aircraft is economical to operate is purely financial as maximum payload is always achievable. It is just a matter of fuel burn and the direct operating cost economics that determine the suitability of the airplane. This region is generally not of interest in regard to a performance study except the fact that the extreme right point of this line is a variable point depending on the airport limited maximum take-off weight allowable (Zone B). This point is sometimes called the "Harmonic Range" of the airplane (Roskam, 1991). It is at this point that the aircraft is most structurally efficient in terms of payload carriage, and "represents the maximum range for the maximum payload" (Mair & Birdsall, 1992).

In Zone B, payload is traded for fuel to attain greater range. The higher the MTOW, the more fuel or payload can be carried. The more fuel carried, the greater the range. Also, the more fuel-efficient the aircraft, the greater the range, or payload, as less fuel is required. To achieve high MTOW, good Take-Off Performance is required. This is the region of greatest interest in terms of Performance. The extreme right point of this zone is where the aircraft is most structurally efficient in terms of fuel carriage, and represents the maximum range with full fuel tanks where a reasonable payload can be carried. Eshelby (2000) refers to this point as Max Economic Range. However, this can be misleading as the reduced payload at this point may in fact not be economical at all.

Zone C is again not a region of interest as it is where the fuel tanks are already full and "the only way to get more range is to unload payload weight" (Roskam, 1991). Roskam as well as Eshelby (2000) appropriately refer to the extreme right point of the graph as Ferry Range as this is what it is best used for. It is not commercially sound to operate in this region, as the sensitivity to payload reductions due to unforeseen circumstances in actual day of flight such as headwinds or take-off restrictions is too great.

By the way of summary, Zone B is where we focus our interest. Between the two maximal points of payload and fuel efficiency is an ideal area that has to be weighed by the airline for optimal operating flexibility. For example, as the airline industry continues to move toward a lower fare structure as a result of enhanced competitive forces, the argument that the payload variable has higher weighting over range in the decision could be advanced. On the other hand longer range may develop exclusivity of a market to an airline that could raise ticket revenues due to limitations in supply.

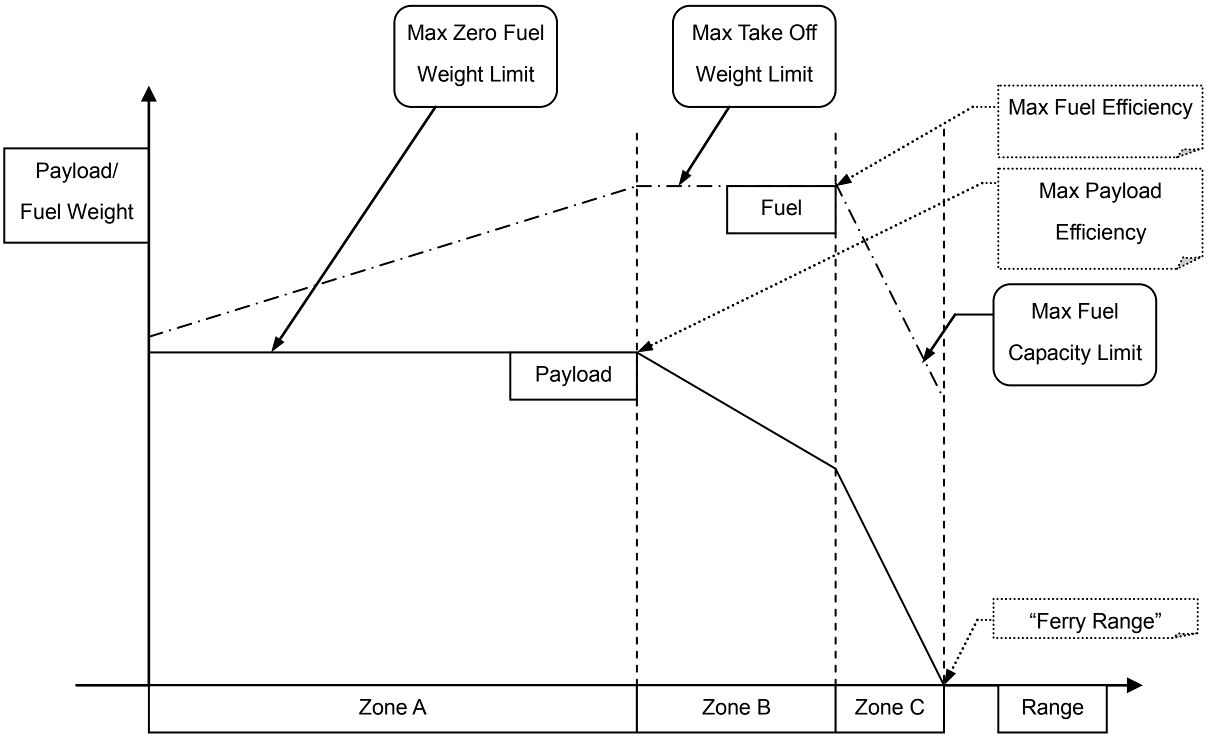

Figure 1. Typical aircraft payload-range chart

2.3. Speed

Our reference is with respect to horizontal cruise speed at an economical fuel burn rate. As with Take-off Performance the basic wing design is usually a trade-off exercise between short runway capabilities against a higher cruise speed. Generally speed for conventional commercial subsonic jet aircraft is limited by the wing sweep (Hale, 1984)

The greater the sweep the greater the delay of high-speed mach buffet onset, and the higher the natural cruise speed. However this usually means a reduction in lift at low speed and vice versa. Good integration of high lift devices such as flaps and slats help mitigate this effect for a weight penalty.

3. The Model

Aircraft are immensely complex. Therefore, it is not practical to consider every possible variable when making procurement decisions. However, we may group variables with common effects together to form factors and use them to evaluate aircrafts.

Hale (1984) offers some insight to a method of selection by using "Figures of Merit" or a weighted system to compare performance data of two aircrafts. As examples, he provides figure of merit groupings as follows:

1. Level Flight
    A. Range
        i. Best mileage (mi/lb)
        ii. Maximum Range (mi)
        iii. Maximum-payload range (lb-mi)
        iv. Best-range airspeed (mph)
    B. Endurance
        i. Minimum fuel-flow rate (lb/h)
        ii. Maximum Endurance (h)
    C. Fastest airspeed (mph)
2. Vertical Flight
    A. Minimum take-off run (ft)
    B. Maximum ceiling (ft)
    C. Climbing flight
        i. Steepest climb angle (deg)
        ii. Maximum rate of climb (fpm)
        iii. Minimum time to altitude (min)
3. Turning Flight
    A. Maximum load factor (*g*'s)
    B. Fastest turning rate (deg/s)
    C. Tightest turn (ft)

We can overlook the last one (Turning Flight), as it applies mainly to Fighter aircraft, and simplify down to five factors below as the main criteria for study. Some of the items are also further used as Measurement Parameters in the later part of this paper. Landing Performance for example could also have been chosen, but generally if an aircraft has good Take-Off characteristics, it also has good landing characteristics since it will have the same assets of engine thrust or wing aerodynamic high lift devices for both phases of flight.

"Effects"	1. Take-Off Performance 2. Fuel Efficiency 3. Speed
"Cause"	4. Power 5. Aerodynamics

The first three variables are the attributes (effects) that we desire from the aircraft, while the latter two are variables that contribute (causes) towards these attributes. As in Figure 1, Zone B, the aircraft payload-range characteristics are defined largely by Take-Off Performance and Fuel Efficiency. For each aircraft these are largely determined by the *Power* and *Aerodynamics* configuration. Power, viewed in the sense of thrust to weight ratio and aerodynamics, viewed in the sense of wing lift and drag minimisation design.

After defining the areas of interest with respect to aircraft performance, in Figure 2, we provide a comprehensive model for assessment of aircrafts. The model will simplify for management consideration of the causes when evaluating aircraft for one or more particular attributes. We cover each factor as follows.

3.1. Take-Off Performance

Take-Off is the first phase of flight starting from the beginning of the useable runway to an altitude 1,500 feet above the runway. The more capable the airplane is of taking off, the more it can satisfy route requirements of payload and range. A short runway reduces the available acceleration capability of the aircraft. An aircraft design may incorporate improved aerodynamics and high lift devices to permit shorter take off rolls. A wing designed for low speed lift capability however may not be suitable for high-speed cruise. Hence retractable high lift devices such as flaps and slats are employed for the low speed phases of flight. Such devices however incur weights that can penalize cruise fuel burn efficiency.

Two other significant factors serve to reduce wing efficiency and these are high temperatures and high airport altitudes (elevation). Both reduce the air density, requiring the aircraft to use more runway length to achieve equivalent lift at higher true airspeeds for lift off compared to lower temperatures or elevations. Take-off climb immediately after take-off is also affected. A reduced take-off climb capability in the first (gear retraction) and second segment (climb portion after gear retraction to level off acceleration height) would incur weight penalties in order that the aircraft can climb above obstacles and minimum regulatory climb gradient requirements. By regulation the climb capability is reflected as a restriction in the final take off weight allowable.

Short runway capability cannot be underemphasized. Even at large multi-runway airports where long runways are available, the ability to take off on shorter runways is a bonus when congestion or contamination is considered. At a large multi-runway airport, the ability to take off and land at runways (or intersections) other than the longest runways gives the operator a time and fuel advantage over others that have to queue in line when the runway capacity is exceeded. "It makes little difference that a 5,000-foot runway can accommodate 30 arrivals per hour if only two flights are able to land on a runway that short. … as the newer regional jets (RJs) replace turboprops, they require longer runways because of the higher speed at which they land. Currently these jets are reducing the overall capacity of certain airports by putting more traffic on the main runways." (Barrer & Swedish, 2000)

"Short runways may negatively impact the economic attractiveness of an airport for an air carrier operating regional jets." (Arnsperger & Campbell, 2000). This same effect applies to all sizes of aircraft and particularly so if runway operations are considered for contaminated situations. Wet, standing water, slush, snow, or ice contamination reduces the effective length of a runway for both take off and landing. Rolling resistance especially, while insignificant on dry runways, can have an exceptional effect on the length of the ground run "when the runway is covered with snow or slush." (Mair & Birdsall, 1992) Hence if an aircraft's dry runway is already marginal, the contaminated situation will be worse.

3.2. Fuel Efficiency

Fuel efficiency is a function of the engine propulsive fuel burn rate as well as the thrust to weight ratio and aerodynamic efficiency of the airplane. Assuming engines to be of similar design, we would expect that the latter factors of thrust to weight ratio and aerodynamic efficiency to have more impact on fuel burn efficiency than design differences when comparing two similar class and generation of aircraft.

In reviewing thrust to weight ratio, a high ratio can indicate an overpowered aircraft with engines that would incur engine weight and corresponding fuel burn penalties. However an optimal ratio would permit the aircraft to climb and cruise more efficiently than an underpowered ratio. For a short-range mission, the ability to climb quickly means a quicker transition to cruise altitude and/or higher cruise altitude where fuel burn rate is much lower. A quick climb rate also means faster vertical as well as horizontal speed for a given flight profile.

Finding the right ratio is also critical for the finance department. Having too large engines means higher unnecessary ownership costs. Having too small engines on the other hand can be costly operationally due to higher wear and tear on the engine. While the focus is often on the engine, the weight component of the aircraft creates similar effects if for example the empty weight of the aircraft is abnormally high for a class of aircraft.

A long-range mission also benefits from having sufficient thrust to weight ratio. For a long-range mission, each unit weight of fuel is critical to the economics of payload versus fuel, as fuel is required to carry fuel, more so than the short-range mission. If the airplane has low thrust to weight ratio, a fully laden airplane will not be able to achieve high initial cruise altitudes. Being stuck at low altitudes will incur higher fuel burn that reduces route economics. “Cruising altitude has a direct effect on fuel weight… For long-range aircraft the minimum fuel requirement dominates.” (Torenbeek, 1988)

Exhaust velocities are higher for an aircraft with low thrust to weight ratio than with high trust to weight ratio. High engine exhaust velocities result in lower propulsive efficiencies due to the higher difference in exhaust and airframe airspeed velocities.

The aerodynamics of the airplane is difficult to quantify. In the climb and cruise portions, the thrust to weight ratios tend to overshadow the effects of aerodynamics. Fuel burn rate per unit of time in cruise is a partial measurement. Another measurement is the fuel burn rate of the airplane in a holding pattern. In a holding pattern, the airplane attempts to burn as little fuel as possible to stay in the air. Regulatory reserve fuel is also often dictated by holding fuel requirements.

We suggest that the aerodynamic design characteristics of the aircraft and perhaps some portion of the power factor largely define fuel efficiency.

3.3. Speed

The speed factor has been described before, as it is also one of the main features defining aircraft performance. As wing design is a typical limitation in cruise speed, we hypothesize that the main effects towards a natural cruise speed is determined largely by the Aerodynamic design characteristics of the aircraft rather than the Power factor.

3.4. Power

As mentioned in the Payload-Range description, the “Power” description is defined largely by thrust-to-weight ratio. But in line with the dynamic measurement focus of the project, a better definition may be the ability of the aircraft to take-off and climb in a short time, as well as the climb altitude capabilities of the aircraft. A way to visualize is to consider Power as the excess energy available for acceleration in any phase of flight. Asselin (1997) for example quotes that the amount of specific excess power available during flight can be used to determine the manoeuvring capability of an aircraft. For example in a climb, both the engine thrust and wing lift contribute to climb rate. But since the wings require engine thrust to be at least equal to drag to maintain level flight (i.e. where lift = aircraft weight), the engine thrust beyond that required for level flight is what provides climb performance.

This Power factor is seen contributing significantly to the Take-Off Performance and to a lesser degree to both Fuel Efficiency and Speed.

3.5. Aerodynamics

This field is complex and normally deals with different phases of flight and conditions as a result of the aircraft's design configuration. However we attempt to generalize the term as a layman would in describing the aircraft flight characteristics. We use this factor as a possible cause effecting Fuel Efficiency, Speed, and Take-Off Performance.

The aircraft performance model is presented in Figure 2. In this model it is hypothesized that Power and Aerodynamics are two major factors that directly affect Speed, Take-Off Performance and Efficiency of the aircraft. In the following we test if the factors can be measured adequately and whether the relationships (the arrows) between the "cause" and "effects" are statistically significant.

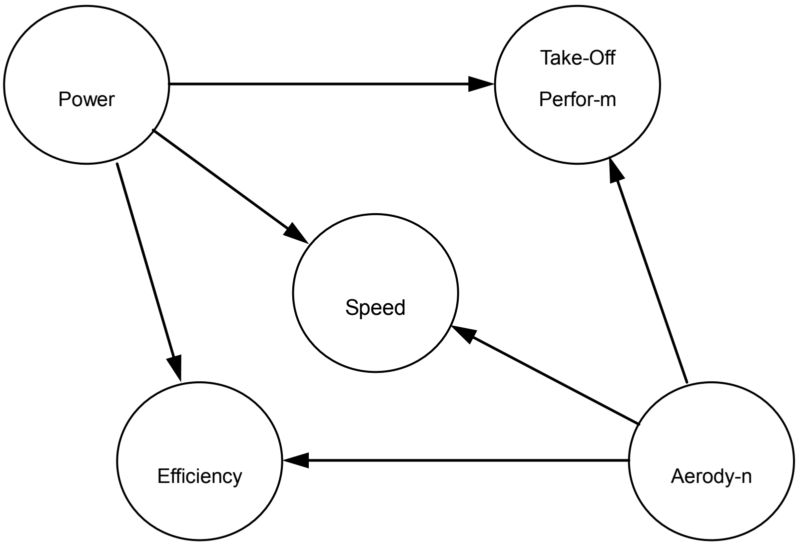

Figure 2. A model for aircraft performance

4. Methodology

Most variables used to assess the above-described model were dynamic measures. The only "static" measure used was "Thrust to Weight" ratio, which was believed to significantly influence dynamic measures.

To obtain the required measures, modern software from the manufacturers was used that allowed simulation of phases of flight in set conditions, rather than actual physical measurements of actual aircraft. This however limited the choice of aircraft for the sample set as such software was available only from two manufacturers, namely Airbus and Boeing (including McDonnell Douglas). The Airbus Performance Engineers Program (WinPEP) and Boeing's Electronic Performance Documents (EPD) can produce simulated results with real databases. Data that had ambiguity over the compatibility of the results between the two types of software (particularly the underlying assumptions) were rejected. Only aircraft of the same genre, i.e. in production today, were selected so as not to have longitudinal error in measuring aircraft designs of different manufacturer visions.

Each "aircraft" sample was actually an aircraft performance model. Two airplanes that look exactly the same may have different power engine thrusts and certified gross weights. Either of these two parameters can create an aircraft that performs differently. Hence this allowed similar model aircraft to be used more than once in the sample set, provided either of the two parameters were different. To maintain reasonable distributions and variety of samples however, same aircraft-engine combinations of different operating weights were limited to eight or less. These and other practical issues resulted in having a sample of 222 different types of performance models. The sample proportions by design manufacturer were Airbus: 88 (40%), McDonnell Douglas: 21 (9%), and Boeing: 113 (51%). This reflected the proportion of commercial aircraft in operation today.

To be able to compare aircraft of different sizes, some of the variables were normalized. For example all weights and measurements that varied with size of the aircraft type were divided by the Maximum Take-Off Weight (MTOW). Variables that did not have dimensions such as Thrust to Weight ratio were accepted as is.

International Standard Atmosphere (ISA) was used except for the TOWTMP variable where ISA+35^{o}C was used to simulate a hot temperature. For climb and descent altitudes, 31,000 ft was used as the standard target or descending-from altitude. Long Range Cruise (LRC) speed defined as 1% less than maximum range speed (Airbus, 2002) was used as standard and representative of real flights. MTOW was used as the defining weight for any measurements such as take-off, climb, holding or descent.

The Partial Least Squares (PLS) method was used to fit the above model. The PLS method is originated by Herman Wold (1985) and according to Jöreskog and Wold (1982), "PLS is primarily intended for causal-predictive analysis in situations of high complexity but low theoretical information." In this case it is not that the theoretical information is low, but certainly the complexity is high and the intent is to simplify the interpretation of the data for the higher management of an airline to make key procurement decisions.

5. The Constructs and Their Coresponding Measures

TAKE-OFF PERFORMANCE is a complex characteristic of the aircraft and is determined largely by both the thrust to weight ratio and aerodynamic configuration of the aircraft. Braking capability is also a hidden quality as it is part of the regulatory requirement for take off that the aircraft be able to stop within the available runway if an engine fails at the critical speed. This construct is measured by the following 3 variables.

1. TOWALT is the altitude limited take-off weight achievable at an airport at 5,000 feet elevation in ISA (International Standard Atmosphere) conditions using optimal flap setting and an infinite runway length (15,000 feet is used as it is beyond the requirements of most aircraft). The 5,000 feet elevation simulates a high airport such as Denver (5,430 feet) where the air is less dense and the aircraft requires more runway length to achieve an equivalent lifting speed to an airport at sea level. The actual take off weight value is divided by MTOW to normalize.

2. TOWRWY is the runway limited take-off weight achievable at an airport at sea level in ISA conditions using optimal flap setting and a runway length proportioned by MTOW. Assuming the range of commercial jet aircraft to be 5,000 feet to 12,000 feet

in length, and the maximum MTOW to be in the range of 1,000,000 lbs, the runway length used for each aircraft is determined by the formula [(MTOW/1,000,000) × 7,000] + 5,000 feet. The actual take off weight value is divided by MTOW to normalize.

3. TOWTMP is the temperature limited take off weight achievable at an airport at sea level in ISA+35 degrees C (or 50 degrees C) conditions using optimal flap setting and an infinite runway length (15,000 feet is used as it is beyond the requirements of most aircraft). The ISA+35 degrees C simulates a high temperature where the air is less dense and the aircraft requires more runway to achieve an equivalent lifting speed to an airport at lower temperatures. "ISA+35" is the normal maximum temperature of the operating envelope of most aircrafts. The actual take off weight value is divided by MTOW to normalize.

EFFICIENCY is a function of fuel burn characteristics of the aircraft in performing its missions. An aircraft may be able to take off with high weights but may not necessarily be fuel-efficient. Fuel burn affects economics and payload. A large fuel requirement would mean high cost and reduced payload and range when the mission is MTOW or fuel capacity Limited. This construct is measured by the following 3 variables.

1. NMCRSFUL indicates how much fuel is burnt for a 538 nm (nautical mile) cruise sector using LRC cruise speed at MTOW in ISA conditions. The value is determined by subtracting a 1,011 nm sector fuel burn from a 473 nm sector fuel burn. This subtraction essentially eliminates the fuel burn for the takeoff, climb, descend, and landing portions. The actual fuel quantity by weight is divided by MTOW to normalize.

2. NMCLBFUL indicates how much fuel is burnt for the climb phase from 1500 feet

(end of take off phase) to a nominal 31,000 feet cruise altitude at MTOW in ISA conditions. The actual fuel quantity by weight is divided by MTOW to normalize.

3. NMHLDFUL is the fuel burnt per hour while holding in clean configuration at 1,500 feet altitude at MTOW in ISA conditions. In the holding phase, the objective is to stay airborne at a minimal rate of fuel consumption. Hence this a good measure of fuel burn efficiency. The actual fuel quantity by weight is divided by MTOW to normalize.

CRUISE SPEED is a design characteristic of the aircraft. These are determined largely by the wing sweep, which helps to delay the onset of supersonic drag, and the thrust available that provides the acceleration available to get to a speed.

1. SPEED is the average LRC flight speed in Knots True Airspeed (KTAS) over a 538 nm cruise sector in ISA conditions at MTOW. This is determined by dividing 538 nm by the difference in flight times between a 1011 nm sector and a 473 nm sector. This difference essentially eliminates the time, speed, and distance components for the takeoff, climb, descend, and landing portions. Selection of the LRC speed incurs the consideration of fuel economy of the aircraft's natural cruising speed rather than raw speed.

POWER is a function of the Acceleration capabilities of the aircraft. These are determined largely by the Thrust to Weight ratio and measured by the following five variables.

1. THRWGT is the thrust to weight ratio, i.e. total sea level static conditions engine thrust divided by the MTOW of the aircraft. Aircraft can be underpowered or overweight for their class. A Thrust to Weight ratio reflects both types of deficiencies.

2. CLBALT is the maximum altitude feet MSL pressure altitude achievable under

Climb Thrust setting at MTOW starting at 1,500 ft above sea level (end of take off phase) in ISA (International Standard Atmosphere) conditions. It is a combination of engine thrust and wing lifting capability that determines the altitude. This measurement may be more related to Power. Values of CLBALT should be more than CRSALT since Climb engine thrust setting is higher than Cruise engine thrust setting but variance should be similar.

3. CRSALT is the maximum altitude in feet MSL pressure altitude achievable under Cruise Thrust setting at MTOW starting at 1,500 ft above sea level (end of take off phase) in ISA conditions. It is a combination of engine thrust and wing lifting capability that determines the altitude. This measurement may be more related to Power. Values of CRSALT should be less than CLBALT since Cruise engine thrust setting is lower than Climb engine thrust setting but variance should be similar.

4. LLCLBTME indicates how much time in minutes is required for the climb phase from 1500 feet (end of take off phase) to a nominal 31,000 feet cruise altitude at MTOW in ISA conditions. The longer it takes to reach the 31,000 feet altitude the weaker the engine. To make the direction of this variable in line with the other indicators of the construct, the actual values in minutes are deducted from 40 minutes.

5. LLTOTME is the time in minutes required for the take off phase, from start at the beginning of the runway to an altitude 1,500 feet above the runway, using maximum take off thrust. The time value is a measure of the acceleration capability of the aircraft. To make the direction of this variable in line with the other indicators of the construct, the actual values in minutes are deducted from 20 minutes.

AERODYNAMICS is a function of the Lift and Drag characteristics of the aircraft. These are determined largely by the design of the wing and devices such as flaps. The following variables were used as measures of this construct.

1. DSCTME is the flight time to descend from 31,000 feet to 1,500 feet MSL pressure altitude in ISA conditions. 31,000 feet is chosen as a nominal cruising altitude (usually between 29,000-45,000 feet). The Descent phase is a good indicator as usually the engines are at idle thrust and the "gliding" characteristics are reflecting the aerodynamic configuration of the aircraft. Per Asselin (1997), a gliding phase is where only the three forces of Lift, Drag, and Weight are acting on the aircraft.

2. APPSPD is the certified final approach (to land) speed in Knots Indicated Airspeed (KIAS) using maximum certified flap configuration at MTOW at sea level in ISA conditions. This speed is a function of the stall speed of the wing in landing configuration, which is affected by the design of the basic wing and supplementary high lift devices such as slats and flaps. These devices are also used in take off and landing but generally more so in the approach and landing phases. The measurements are better reflected in these phases than take off since the deflection and corresponding effects of the devices are greater, and the power settings and effects of engine thrust are lower.

3. LNDDST is the certified landing distance in feet using maximum certified flap configuration at MTOW at sea level in ISA conditions. While braking ability does have effects here, the distance required to land is composed of a flare portion before touchdown, and the distance is directly a function of the approach speed. Hence the elements of APPSPD also apply.

6. Findings

The model presented in Figure 2 was tested using the PLS (Partial Least Squares) method. Figure 3 provides an estimate of the factor loadings, the path coefficients and in brackets the weights used for construction of the factors.

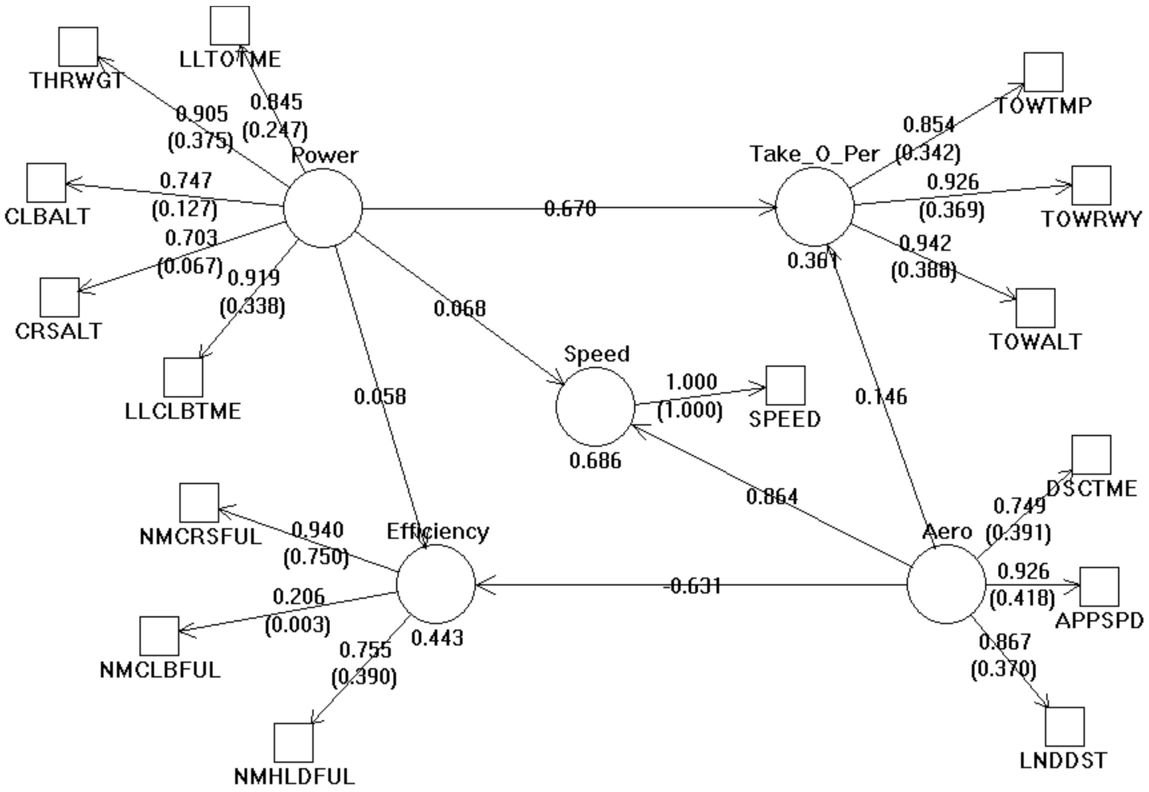

Figure 3. Estimates of the parameters

The path coefficients, which reflect the strength of the relation among the factors, along with their corresponding t-statistics are given in Table 2.

Table 2. Path coefficient and the t-statistics for the model

Path Coefficients (Entire Sample Estimate):

	Take_O_P	**Power**	**Aero**	**Efficiency**	**Speed**
Take_O_P	**0.0000**	**0.6700**	**0.1460**	**0.0000**	**0.0000**
Power	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
Aero	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
Efficien	**0.0000**	**0.0580**	**-0.6310**	**0.0000**	**0.0000**
Speed	**0.0000**	**0.0680**	**0.8640**	**0.0000**	**0.0000**

T-Statistic

	Take_O_P	**Power**	**Aero**	**Efficiency**	**Speed**
Take_O_P	**0.0000**	**17.0926**	**2.3817**	**0.0000**	**0.0000**
Power	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
Aero	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
Efficien	**0.0000**	**0.9551***	**-14.5261**	**0.0000**	**0.0000**
Speed	**0.0000**	**1.6082***	**27.5281**	**0.0000**	**0.0000**

*** Not statistically significant (less than 2.0)**

For the factor of Take-Off Performance, we note that Power (0.670) has a much more significant contribution than Aerodynamics. And in fact this is borne out in practice where later generation aircraft dispense with complex high lift devices at the expense of take-off capability. However a common technique to recover the performance is by simply up-rating the engine thrust, such as on the Airbus A321.

Rated thrust for takeoff and climb (Our Power measurements) however do not reflect well the thrust at cruise. For example the manufacturers can up-rate an engine on an underpowered aircraft just to improve take-off performance, but in cruise the up-rated thrust is not apparent as fuel consumption rate determines the natural economic cruise speeds.

Roskam (1991), states that the variables that affect the take-off distance most strongly, are the take-off thrust-to-weight ratio, take-off wing loading, and the maximum lift coefficient. The first two are related to the engine thrust, while the latter refers to lift coefficient that can be improved by high lift devices. Hale (1984) confirms the same ideas in an extreme case where a “low wing loading, a high lift coefficient, and a high thrust-to-weight ratio” characterizes a STOL (Short Take-Offs and Landings) aircraft. High lift devices however can also increase drag, hence the thrust or power factor can be a cleaner solution though there are economic tradeoffs such as higher ownership and maintenance costs of engines.

On the A321 for example, to achieve comparable performance to its shorter fuselage A320 cousin, Airbus introduced double-slotted flaps in place of single slotted flaps and up-rated engines to achieve a higher lift coefficient and similar thrust-to-weight ratios with the same sized wing and engines despite a 13% increase in weight and reduced ground rotation angle due to the increased length of fuselage. (Asselin, 1997)

For the factor of fuel Efficiency, we note that the Power factor has less impact (not statistically significant) than the Aerodynamics factor (-0.631). The negative coefficient makes sense as the lower the value of measures such as APPSPD (Approach Speed) and LNDDST (Landing Distance) the higher or more lift efficient the wing is.

For the Speed factor, we see that the Aerodynamics factor (0.864) is more important than the Power factor, which is not statistically significant. It is interesting to interpret that common considerations of high power engines do not necessarily relate to high speeds. In fact, commercial jet engines typically have a cruising thrust level equal to a fraction (10-20%) of that at take-off at sea level. As (Eshelby, 2000) mentioned "In cruising flight, the rate of climb is zero and the thrust power required is equal to drag power" The main limitation is the wing aerodynamics, which should be reviewed when selecting an aircraft for qualities of high speed. As Torenbeek (1988) states "Flight Speed Variation has a major effect … on the design of the wing (sweep angle), … engine s.f.c. (specific fuel consumption)…" . Since we are evaluating Long Range Cruise Speed, and not Maximum Speeds, the wing design takes precedence because the main effect of the engine is only related to the fuel consumption rate, which is already set by the definition of LRC.

Hence for both Efficiency and Speed, there is an implication that the Aerodynamics of the airplane should be analyzed more thoroughly than today's practices reflect. The sample aircraft performance models reflect aircraft that have high thrust to weight ratios, but this can be a result of up-rated engines that only provide additional thrust at take off rather than during the climb and cruise phases of flights.

7. Conclusions and Future Research

This study utilized SEM techniques to model aircraft performance and provided some alternative measures for evaluation of commercial aircraft. The variables used in this study were obtained by measuring various characteristics of three genres of aircraft. The number of aircraft types within a particular genre is limited and an aircraft has numerous characteristics, which can be measured for evaluation. However, these measures are highly correlated. Hence, one may choose a limited number of them based on the factors that are of interest.

Once the factors are selected, the methodology demonstrated here may be used to evaluate aircraft performance based on dynamic measures. In this case our particular interest was in the causal factors of Take-Off Performance, Fuel Efficiency, and Speed. For the former, the Power factor was the most significant, while the latter two indicated that the Aerodynamics factor was more important. These results direct an aircraft procurer to look more closely at the Power and Aerodynamics characteristics of the aircraft when selecting an aircraft for an intended mission, or in our case a desire for operational flexibility.

In this study, a method for assessment of aircraft was developed. However, the scope was limited in nature for a particular objective. There are no limitations on using the same methodology for other types of objectives. For example suitability of particular aircraft for other aviation applications such as banking ability to do low speed low radius turns to avoid weight limiting obstacles, or high altitude or surveillance type missions.

We used only a fraction of possible measures in this study. Brake energy values for example were not analyzed. The Take-Off Performance area could have been broken down further into the accelerate-go, accelerate-stop and climb phases, for a more detailed analysis.

A further extension to the study of operational flexibility would be to review the effect of load factors and fuel sensitivity with respect to varying load factors or Zero Fuel Weight. Passenger comfort is another factor that varies with load factor in competitive markets. As Janić (2000) mentioned “the airlines always aim to keep the load factor at a level providing at least nonnegative profits, … when load factor is relatively high, say between 0.8 and 0.9,… the quality of service provided to the passengers, … privacy and personal comfort will reduce” .

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