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Impact of Aircraft Performance Characteristics on Air Traffic Delays

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Abstract

Air transportation has been suffering for decades from delays caused by air traffic congestion. This paper presents the effect of aircraft performance differences on air traffic delays. Rate of climb and cruising speeds of 70 different aircraft types are compared to demonstrate performance differences in the current transport aircraft fleet. The effect of these performance differences on air traffic delays is proved by a deterministic calculation of delays for a departure queue consisting of 3 different types of aircraft. In addition, it is shown how a slower cruising speed can cause excessive fuel consumption in an aircraft that is obliged to follow a slower aircraft in an enroute queue. It is concluded that air traffic flow management units should take into account aircraft performance differences for sequencing, and that aviation authorities should consider establishing minimum performance requirements for each altitude for each aircraft category.

Key words: Aircraft performance, Air traffic management, Air traffic control, Air traffic delay, Flight profile.

Introduction

The phenomenal worldwide growth in air traffic poses a serious air traffic management (ATM) system capacity problem, especially in Europe and the USA. The ATM system ensures the safe, expeditious, orderly and economical flow of flights. Separation minima are used by air traffic managers to ensure safety by establishing the minimum allowable separation that should exist between multiple aircraft in the various phases of flight. However, airspace capacity, and consequently ATM capacity, is constrained by these separation minima (Reynolds and Hansman, 2000) along with other constraints such as air traffic managers, pilots (human performance) and equipment used in the system (radar, navigation aids). Inadequate airspace capacity results in delays of flights.

ATM influences the vertical separation of aircraft by assigning different altitudes, longitudinal separation by providing an interval expressed in time or distance between aircraft on the same, converging, or crossing courses, and lateral separation by assigning different flight paths (FAA, 2001). International separation minima standards are drawn up by the International Civil Aviation Organization (ICAO). These standards are calculated by considering collision risk and aircraft wake turbulence.

Wake turbulence is caused by a pair of counter rotating vortices trailing from the wing tips of aircraft. It is a function of the weight, airspeed and wing design of the aircraft. The vortices from larger aircraft pose problems for aircraft encountering them. Turbulence generated within the vortices can damage aircraft if encountered at close range. A wake encounter can be catastrophic. In 1972 at Fort Worth a DC-9 approached too close to a DC-10 (2 miles behind), rolled, caught a wingtip, and cart-wheeled, coming to rest in an inverted position on the runway. All those aboard, were killed (FAA, 2001).

Due to the application of separation minima in consideration of collision risk and wake turbulence, the trajectories of all aircraft in flight within the airspace are constrained by the trajectories of others. The trajectory of an aircraft is the net result of all control inputs to it by the pilot, but it is constrained by the performance of the aircraft. Therefore, the performances of all aircraft within the same airspace are constrained by the performances of the others within the airspace.

For the last 20 to 30 years, considerable research has been conducted in the field of ATM to enhance system capacity in order to improve the ATM objectives of safety, efficiency and economy. These research studies have covered all key elements of ATM, such as airspace, technical equipment, aircraft and human factors. However, most research on aircraft elements has concentrated on trajectory prediction for conflict detection and resolution, and on the installation of new equipment to meet 21^{st} century Communication, Navigation and Surveillance ATM (CNS/ATM) requirements, but not on aircraft performance differences. This paper presents the impact of aircraft performance differences on air traffic delays.

Air Traffic Delays

Delay has traditionally been one of the key indicators of ATM system performance (Bolczak and Hoffman, 1997) because of the economic losses incurred due to delays. The costs caused by delays are quantified by Eurocontrol:

a) 5.73 billion euros/year produced by air traffic control delays (1999);

b) $ 2 billion/year produced by longer trajectories due to the fixed airways network (in Europe);

c) $ 10 billion/year due to air traffic control actions that generate deviations from optimal aircraft flight profiles (Dell'Olmo and Lulli, 2002).

There are several definitions of delay. It is generally defined as the difference between the planned and actual times of operations. Another useful working definition of delay is the additional time required for a flight operation, from the time the flight is ready to depart to the time it arrives at the destination gate, over the time that would have been required if it were the only aircraft in the sky. Recently, the Federal Aviation Administration (FAA) has worked with the airlines to develop a standard definition for aviation delays (Bolczak and Hoffman, 1997). There are 2 types of delay: ground delay and airborne delay.

According to the US Department of Transportation Task Force (GAO, 2001), circumstances within an airline's control, extreme weather, circumstances within the (national) aviation system, and late flight arrivals are the causes of flight delays.

Airline flight schedules are particularly sensitive to individual flight delays because of the manner in which operating resources are linked together. Among the connective resources affected by delayed flight operations are crews, aircraft, passengers and gate space. Due to this branching connectivity, a delay in one flight tends to propagate rapidly down-line to many others (Beatty and Berry, 1998).

Aircraft Performance

The mission profile of a flight is shown in Figure 1. Every aircraft flies a similar mission profile under ATM, airline planning and aircraft performance constraints. Flight profile also defines the trajectory of the aircraft. The performance of an aircraft at each phase of this flight mission, especially during climb and cruise, is vital as regards ATM. Since the trajectories, of all aircraft within same airspace interfere with each others' trajectories causing congestion, it is normal to have delays at each phase of these flight missions for every aircraft. In order to provide a better understanding of how aircraft performance influences ATM performance, climb the and cruise characteristics of aircraft are briefly reviewed here. Detailed aircraft performance calculations can be found in any flight mechanics or aircraft performance textbook.

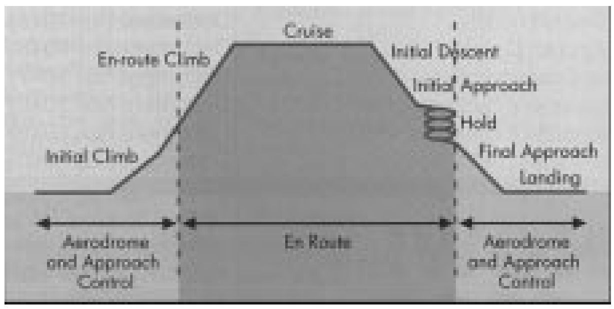

Figure 1. Flight profile (Lewis, 1995).

Climb Performance

Climb performance of aircraft is characterized by the rate of climb and the climb angle. The rate of climb is a function of the excess power and acceleration of the aircraft:

$$v = \frac{(T-D)V}{W} - \frac{V}{g}\frac{dV}{dt} \tag{1}$$

For steady state climb of a turbojet/fan aircraft, the rate of climb is

$$v = \frac{(T-D)V}{W} \tag{2}$$

and for a propeller aircraft

$$v = \frac{\eta P - DV}{W} \tag{3}$$

There are three climbing flight conditions:

a) Steepest climb,

b) Fastest climb,

c) Economical climb.

Steepest climb is climbing flight at the maximum flight angle. Fastest climb is synonymous with the climb at the maximum rate of climb and is of much greater interest than steepest climb. Fastest climb requires the minimum time to climb to a specific altitude, which is of importance to air traffic controlllers, who must keep the intervening airspace clear of traffic. Furthermore, to a first approximation, fastest climb requires the smallest amount of fuel, thus increasing the amount available for cruise. Most economical climb uses the smallest amount of fuel. When the actual variations in thrust and specific fuel consumption are considered along with the compressibility effects of high speed on the performance of the engine, the airspeed for most economical climb, is lower than that for fastest climb but is much closer to the fastest climb airspeed than to the steepest climb airspeed. It is so close that most aircraft do not distinguish between the two climb regimes, and fly the fastest climb whenever possible (Hale, 1984). It is obvious that airlines will prefer economical climb if ATM circumstances permit them.

Cruise Performance

There are 3 main cruise flight conditions from the aircraft design point of view. These are:

a) Constant altitude-constant lift coefficient flight,

b) Constant air speed-constant lift coefficient flight,

c) Constant altitude-constant air speed flight.

When flight is conducted under the jurisdiction of air traffic control regulations, constant altitude-constant airspeed cruise flight is applied (Hale, 1984). For propeller aircraft, the constant altitude-constant airspeed cruise range is

$$R = \frac{2\eta E_m}{c_P}\left[\arctan 2\frac{\sqrt{k/C_{D_0}}W_0}{\rho V^2 S} - \arctan 2\frac{\sqrt{k/C_{D_0}}W_1}{\rho V^2 S}\right] \tag{4}$$

and, for the turbojet aircraft:

$$R = \frac{2VE_m}{c_T}\left[\arctan 2\frac{\sqrt{k/C_{D_0}}W_0}{\rho V^2 S} - \arctan 2\frac{\sqrt{k/C_{D_0}}W_1}{\rho V^2 S}\right] \tag{5}$$

In Eqs. (4) and (5), W_0 is the weight of the aircraft at the beginning of the cruise flight and W_1 is the weight of the aircraft at the end of the cruise flight. Range equations show that the cruise range of an aircraft is dependent on its physical characteristics such as weight, wing area, and specific fuel consumption; aerodynamic characteristics such as maximum lift to drag ratio, parasite and induced drag coefficients and lift coefficient; and operational characteristics such as airspeed and altitude. The lift coefficient and airspeed are the only 2 control variables that can be managed within their limits by the pilot. The flight altitude of the aircraft is controlled by the lift coefficient. The air traffic controller uses radar to assess the traffic situation and communicates with the pilot to give speed, altitude and heading instructions to keep the aircraft separate from the others. Therefore, ATM can only impose the control variables of the range equation.

Performance Comparison of Current Aircraft

Before presenting the implications of aircraft performance differences, it will be useful to present a performance comparison of current aircraft. For this purpose, aircraft performance data were taken from the European Organization for the Safety of Air Navigation (Eurocontrol) "Aircraft Performance Summary Tables for BADA (The Base of Aircraft Data)" (Eurocontrol, 2000) document. This presents tabulated performance data for the 71 different aircraft types modeled by the BADA. For each aircraft type, the performance tables given in the document specify the true air speed, rate of climb/descent and fuel flow for conditions of climb, cruise and descent at various altitudes. Based on these data, climb and cruise performances of 41 turbojet/fan and 29 propeller aircraft are compared. Only the performance of fighter aircraft in the document is excluded.

Comparison of Climb Performances

The climb performance of aircraft, particularly at maximum take-off weight, is especially important for the ATM performance within the terminal areas. Aircraft with best climb performance would keep the terminal area less busy.

Evaluation of the BADA Aircraft Performance Summary tables shows that there is a rate of climb difference of 126% between the fastest climbing and slowest climbing turbojet aircraft at mean sea level (Figure 2). The slowest climbing jet aircraft is the Airbus A340-200, while the fastest climbing aircraft is the Falcon 900 (F900) at mean sea level conditions. The rate of climb difference reaches 395% among the fastest climbing and slowest climbing propeller aircraft, including turboprops and pistons (Figure 3). For lower flight altitudes the slowest climbing aircraft is the Piper Cherokee/Archer/Dakota/Warrior (P28A) series. This series is powered by piston engines. When turbojet/fan and propeller aircraft are evaluated together, the rates of climb of 70 aircraft vary between 720 feet/min and 3,570 feet/min at mean sea level. It is evident that the slowest climbing aircraft would keep the terminal area busy 5 times busier than the fastest climbing aircraft.

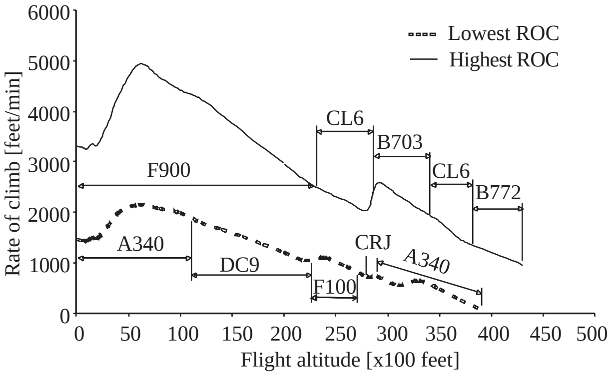

Figure 2. Lowest and highest rate of climbs for 41 turbojet/fan aircraft.

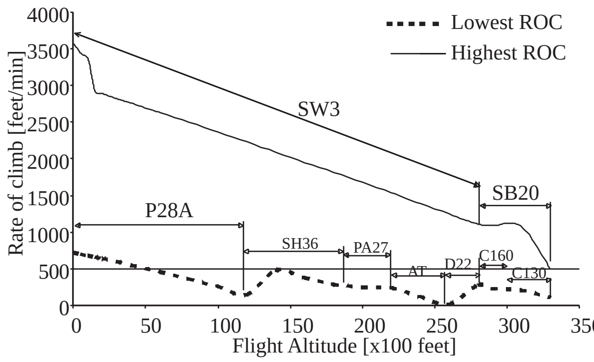

Figure 3. Lowest and highest rate of climbs for 29 propeller aircraft.

Comparison of Cruise Performances

Since propeller aircraft and jet aircraft use different flight altitude ranges for cruise flight, cruise performances are evaluated separately. The cruising speed of turbojet aircraft varies between 314 and 503 knots above 29,000 feet and up to 41,000 feet. The difference between the cruising speeds of the slowest aircraft and the fastest aircraft is 60% at 29,000 feet. This difference decreases to 35% at 37,000 feet (Figure 4). Considering the cruising altitudes above 25,000 feet that are generally used by turbojet/fan aircraft, the Boeing (formerly McDonnell Douglas) MD-11 (MD11) and Boeing 747-400 (B744) are the fastest cruising aircraft. Cessna 550/560 Citation (C550 and C560) business jets are the slowest cruising aircraft. The F900 is the slowest cruising aircraft at 45,000 feet. However, this is not important, because 45,000 feet is not a congested altitude and most aircraft are not able to reach this altitude for cruising. Propeller aircraft rarely fly above 30,000 feet. The difference in cruising speeds of propeller aircraft varies between 63% and 143% from mean sea level to 29,000 feet. The difference is 63% to 90% for altitudes above 18,000 feet up to 29,000 feet (Figure 5). Within this altitude range, cruising speeds of propeller aircraft vary between 185 and 375 knots, although the speeds of turbojet/fan aircraft vary between 260 and 505 knots. For lower altitudes, the slowest propeller aircraft are piston-powered aircraft such as the P28A, Piper PA-34 Seneca (PA34) and Piper Aztec (PA27), while the turboprop powered Dornier 328 (D328) is the fastest aircraft. For higher altitudes, the Dornier 228 (D228) and C-160 Transall (C160) are the slowest aircraft. The fastest propeller aircraft at higher altitudes are the Saab 2000 (SB20) and the C-130 Hercules (C130). The cruising speed differences between propeller aircraft and turbojet/fan aircraft for altitudes above 20,000 feet up to 29,000 feet are very important, especially for routes where short range turbojet/fan and medium to long range turboprop aircraft fly at the same flight altitudes.

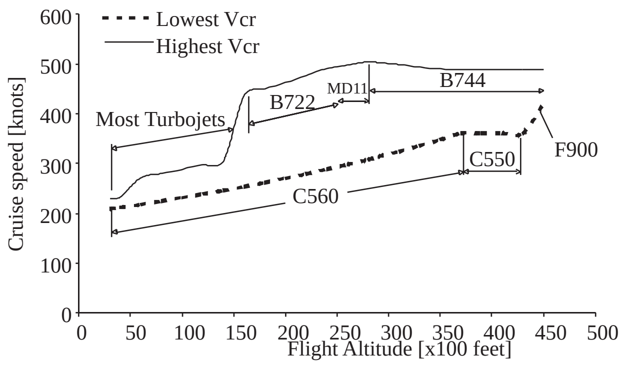

Figure 4. Slowest and fastest cruising speeds for 41 turbojet/fan aircraft.

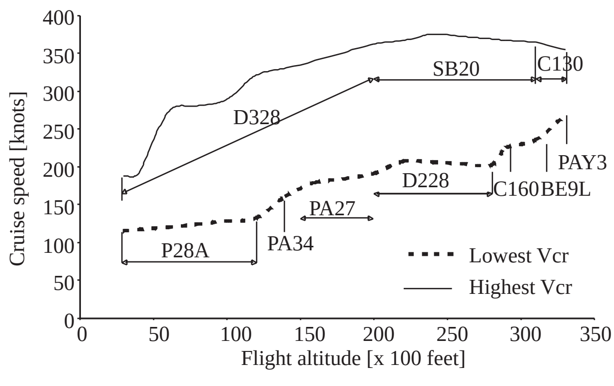

Figure 5. Slowest and fastest cruising speeds for 29 propeller aircraft.

Evaluation of the aircraft performance data presented by the BADA database shows that there are significant performance differences among aircraft that may fly at similar altitudes. A Falcon 900 business jet may be obliged to climb behind an Airbus A340-200 on the same standard instrument departure route by reducing its rate of climb by about 50%. On the other hand, a Boeing 747-400 may be slowed down from 480 knots cruising speed to 360 knots behind a Cessna Citation.

Delay Analysis

To study the impact of aircraft performance characteristics on air traffic congestion, a traffic condition is assumed such that 2 heavy and long range and 1 medium weight and medium range jet transport aircraft filed flight plans to depart at the same time from a single runway airport to fly the same initial route segment of 250 nautical miles. Departure sequencing is assumed in ascending order of performance, from lower performance aircraft to higher performance aircraft, so that lowest performance aircraft would take off first. The rate of climb and cruise speed variations of these aircraft with altitude are given in Figures 6 and 7, respectively. Aircraft weight data are given in Table 1. Delays for given traffic condition are calculated by using a deterministic aircraft separation model. The ICAO separation criteria used in the model are given in Table 2.

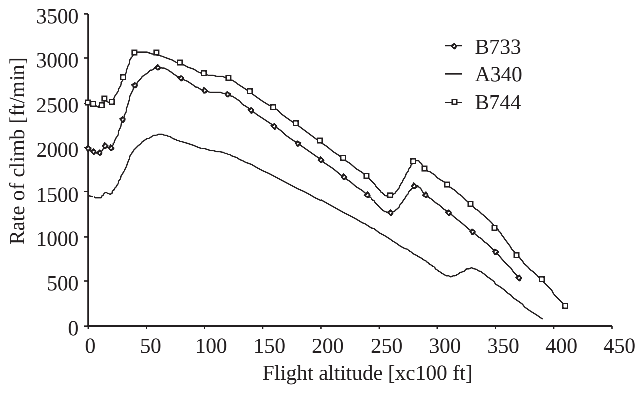

Figure 6. Rate of climb variations for aircraft types used in the model.

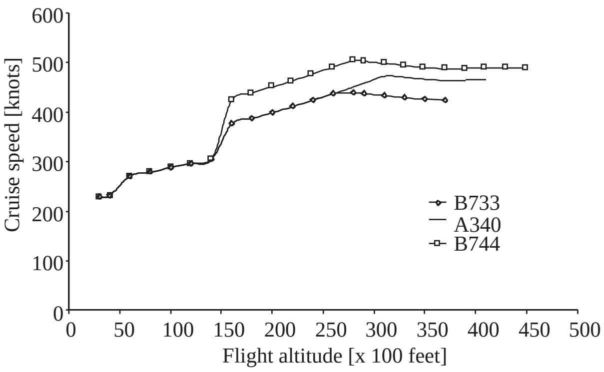

Figure 7. Cruise speed variations for aircraft types used in the model.

Table 1. Aircraft weight data used in the model.

Aircraft	Weight [kg]		
	Low	Nominal	High
A340	156,000	200,000	253,500
B733	38,280	54,000	62,800
B744	216,000	300,000	372,000

Deterministic Aircraft Separation Model

Consider 2 aircraft flying close on the same track. Each aircraft has an elliptical protection zone (Figure 8). The horizontal length of the elliptical protection zone is the longitudinal or wake turbulence separation distance defined by ICAO regulations. The height of the elliptical protection zone is the vertical separation distance. Thus, for an aircraft, the protection zone equation is

$$\frac{(x - x_i)^2}{s^2} + \frac{(h - h_i)^2}{s_v^2} = \frac{1}{4} \qquad (6)$$

where, "i" shows the i-th aircraft on the track, and s and s_v are the longitudinal or wake turbulence, and vertical separation distances, respectively. The separation distances are given in Table 2. x is the horizontal distance from any reference point. h is the flight altitude. The distance between 2 aircraft is

$$\sqrt{(x_i - x_{i+1})^2 + (h_i - h_{i+1})^2} \qquad (7)$$

Protection zones of aircraft pairs should never intersect each other at any moment of flight. Thus from Eqs. (6) and (7),

$$\sqrt{s_v^2(x_i - x_{i+1})^2 + s^2(h_i - h_{i+1})^2} \geq s s_v \qquad (8)$$

In order to avoid intersection of protection zones, aircraft should adjust their flight speeds. If the slowest aircraft is flying at its maximum speed and is being followed by a faster aircraft, then the faster aircraft should slow down. Depending on flight phase, both rate of climb and/or flight speed may be reduced.

Table 2. ICAO separation criteria (ICAO, 1984).

Wake turbulence separation		Separation minima
Aircraft categories		
Leading aircraft	Following aircraft	
Heavy	Heavy	7.4 km (4.0 nm)
W > 136,000 kg	Medium	9.3 km (5.0 nm)
	Light	11.1 km (6.0 nm)
Medium	Heavy	5.6 km (3.0 nm)
7,000 kg < W ≤ 136,000 kg	Medium	5.6 km (3.0 nm)
	Light	9.3 km (5.0 nm)
Light	Heavy	5.6 km (3.0 nm)
W ≤ 7,000 kg	Medium	5.6 km (3.0 nm)
	Light	5.6 km (3.0 nm)
Vertical separation		1,000 ft

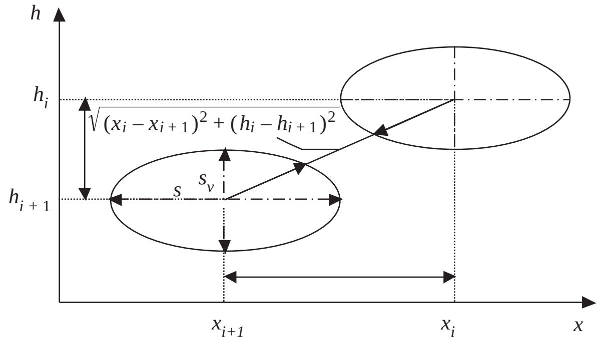

Figure 8. Protection zones and separation between 2 aircraft.

Calculation of Aircraft Trajectories

For each aircraft, BADA Aircraft Performance Summary Tables specify the speed and rate of climb for conditions of climb and cruise at various flight levels. For the climbing phase, to determine the climb time and horizontal flight distance of an aircraft from the BADA Performance Table, it is assumed that the rate of climb decreases linearly with altitude between 2 succeeding flight altitudes where rate of climb values are given. This assumption is correct according to McCormick (1979). Thus,

$$v_{i,j} = a_{i,j} - b_{i,j} h_j \qquad (9)$$

where $v_{i,j}$ is the rate of climb of the i-th aircraft at j-th flight altitude. Therefore, climb time from the j-th altitude to the $j+1$-th altitude is

$$(\Delta t_{j,j+1})_i = -\frac{1}{b_{i,j}} \ln \frac{v_{i,j+1}}{v_{i,j}} \qquad (10)$$

Horizontal flight distance during this time interval is

$$(\Delta x_{j,j+1})_i = \frac{V_{i,j}+V_{i,j+1}}{2} \sqrt{1 - \left(\frac{v_{i,j}+v_{i,j+1}}{V_{i,j}+V_{i,j+1}}\right)^2} (\Delta t_{j,j+1})_i \qquad (11)$$

where $V_{i,j}$ is the flight speed of the i-th aircraft at the j-th flight altitude. By applying Eqs. (10) and (11) to the BADA Aircraft Performance Summary Tables, approximate climb trajectories of the aircraft are determined as functions of time in 2 polynomial forms:

$$x(t) \text{ and } h(t) \qquad (12)$$

Coefficients of the climb trajectory polynomials are given in Table 3 for each simulation aircraft. For the cruising phase of the flight, speed and altitude are constant. Therefore,

$$x_i(t) = V_{i,j} t \text{ and } h_i(t) = h_{i,j} \qquad (13)$$

Algorithm for the Computation of Performance Delays

A set $I = \{i | i = 1, 2, \ldots, n-1\}$ of n flights has to depart from a single-runway aerodrome within a given time interval T. All flights have to fly the same initial route segment of R nautical miles that starts from the runway threshold. Let $\tau \in \mathfrak{R}$ be the real time. Let the pilots have filed flight plans for take-off at the same time. However, because there is only a single runway available, Air Traffic Control (ATC)

Table 3. Aircraft climb trajectory equations.

Aircraft	Horizontal distance coefficients $x(t) = a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5 + a_6t^6$ [nm]					
	a_1	a_2	a_3	a_4	a_5	a_6
A340	2.6327	0.2017	-0.0034	0.00002	0	0
B733	2.3129	0.3826	-0.0119	0.0001	0	0
B744	2.5897	0.419	-0.0132	0.0001	0	0
	Vertical distance (altitude) coefficients $h(t) = b_1t + b_2t^2 + b_3t^3 + b_4t^4 + b_5t^5 + b_6t^6$ [ft]					
	b_1	b_2	b_3	b_4	b_5	b_6
A340	957.963275	134.808181	-13.570367	0.568434	-0.011713	0.000096
B733	2204.356779	-16.898229	-1.238618	0.021988	0	0
B744	2426.831396	-39.780038	-0.33538	0.010662	0	0

has to sequence the flights according to their readiness for take-off by considering the wake turbulence separation requirements, which are given in Table 2. Thus,

$$\begin{array}{rcll} W_i > 136,000 & \text{and} & W_{i+1} > 136,000 & s_{i,i+1} = 4 \\ W_i > 136,000 & \text{and} & 7,000 < W_{i+1} \leq 136,00 & s_{i,i+1} = 5 \\ W_i > 136,000 & \text{and} & W_{i+1} < 7,000 & s_{i,i+1} = 6 \\ 7,000 < W_i < 136,00 & \text{and} & W_{i+1} > 136,000 & s_{i,i+1} = 3 \\ 7,000 < W_i < 136,00 & \text{and} & 7,000 < W_{i+1} \leq 136,00 & s_{i,i+1} = 3 \\ 7,000 < W_i < 136,00 & \text{and} & W_{i+1} < 7,000 & s_{i,i+1} = 5 \\ W_i \leq 7,000 & & & s_{i,i+1} = 3 \end{array} \tag{14}$$

The resulting initial take-off separation time between 2 departing aircraft is

$$\Delta t_{i,i+1} = \left(\frac{s_{i,i+1}}{V_{0_i}} \right) \tag{15}$$

where $\Delta t_{i,i+1} \in I$ and V_{0_i} is the climb speed of the i-th aircraft at runway elevation altitude. Therefore, the estimated departure times of the flights will be

$$t_{0_i} = \begin{cases} 0 & \text{for} \quad i = 1 \\ \sum_{j=2}^{i} \Delta t_{j-1,j} & \text{for} \quad i > 1 \end{cases} \tag{16}$$

Then the real departure times are

$$t_{R_i} = \begin{cases} 0 & \text{for} \quad i = 1 \\ t_{R_{i-1}} + (t_{0_i} - t_{0_{i-1}}) + \delta t_{p_i} & \text{for} \quad i > 1 \end{cases} \tag{17}$$

where $\delta t_{p_i} \in I$ is the delay time due to performance differences. Initially, $t_{R_i} = t_{0_i}$ for all flights. For any real time τ, the flight time of each flight since take-off will be

$$t_i = \begin{cases} \tau & \text{for} \quad i = 1 \\ 0 & \text{for} \quad i > 1 \quad \wedge \quad \tau - t_{R_i} < 0 \\ \tau - t_{R_i} & \text{for} \quad i > 1 \end{cases} \tag{18}$$

The location of each aircraft in the vertical plane along the initial route segment will be

$$\begin{array}{llll} \text{For} \quad t_i \leq t_{cl_i} & x_i(t_i) = \sum_{k=1}^{5} a_{k_i} t_i^k & \wedge & h_i(t_i) = 100 \sum_{k=1}^{6} b_{k_i} t_i^k \\ \text{For} \quad t_i > t_{cl_i} & x_i(t_i) = x_{cl_i} + V_i(t_i - t_{cl_i}) & \wedge & h_i = H_{cr_i} \end{array} \tag{19}$$

where t_{cl_i} is the climb time to the cruise altitude, x_{cl_i} is the distance to climb to the cruise altitude, and H_{cr_i} is the cruise altitude. Separation between 2 aircraft for any aircraft pair can be checked by Eq. (8)

$$\sqrt{s_v^2 (x_i - x_j)^2 + s_{i,j}^2 (h_i - h_j)^2} \geq s_{i,j} s_v \, \text{where} j > i \tag{20}$$

If the given condition is not satisfied, then there will be conflict between 2 aircraft. In order to avoid conflict, the departure time of the second aircraft of the aircraft pair must be changed by increasing δt_{p_i}. When δt_{p_i} is changed, then the flight times and locations of each aircraft must be recalculated. After the last aircraft reaches the horizontal distance R, total performance delays can be calculated:

$$\Delta t_p = \sum_{i=1}^{n} \delta t_{p_i} \tag{21}$$

Calculated Delay

Delays of flights are calculated by using the separation model summarized by Eq. (8), trajectory equations given by Eqs. (12) and (13), and the algorithm given by Eqs. (14) to (21). Since all the aircraft have initially requested to depart at the same time and there is only 1 runway, different estimated departure times are applied to the flights. Estimated departure times of all aircraft are given in Table 4, along with the delays of each aircraft. An initial delay occurs for at least 2 of the flights due to runway capacity limitation. However, an additional delay is required for the B744 because of the performance differences between it and the other 2 aircraft that will depart before it. If the B744 is not delayed on the ground before departure for an additional 4 min, the trajectory of this aircraft will conflict with the trajectories of the A340 and the B733 within the 250 nautical mile initial route segment. The slower climb and cruise speed of the B744 can represent a solution to avoid this ground delay of 4 min. However, for a high performance aircraft, there are excessive fuel consumption consequences of flying a trajectory different from the optimal.

Effect of Reduced Cruising Speed on Cruise Fuel Consumption

According to the BADA Aircraft Performance Summary Tables (Eurocontrol, 2000), the optimum cruise speeds of the B733 and the the B744 at 31,000 feet are 434 knots (Mach 0.74) and 499 knots (Mach 0.85) respectively. If the B744 is not delayed on the ground for an additional 4 min, this aircraft will be constrained to fly at 434 knots in order to follow the B733 without causing a conflict; 434 knots is 87% of the optimum cruise speed of a B744. Cruise fuel consumption of the B744 at 31,000 feet is analyzed by using the physical and aerodynamics characteristics given in Table 5, and the constant altitude–constant airspeed range equation (5). It is assumed that the sea level specific fuel consumption of the engines is 0.75 (kg-fuel/kg-thrust per hour). It is also assumed that the specific fuel consumption of the engines varies with altitude as follows (Ananthasayanam, 2000):

$$c_T = (c_T)_0 \sigma^{0.2} \tag{22}$$

The variation of the ratio of fuel consumption to the economical cruise speed fuel consumption with the ratio of airspeed to the optimum cruising speed at 31,000 feet is given in Figure 9. Flight at a 13% reduced speed results in excess fuel consumption of about 4%. A 20% reduction in cruising speed causes a 9% increase in fuel consumption.

Table 4. Calculated delays.

	Cruise altitude [feet]	Departure Time			Delays [minutes]		
		PlannerPlanned	Estimated	Real	Runway capacity	Performance differences	Total
A340	31,000	0:00	0:00	0:00	0:00	0:00	0:00
B733	31,000	0:00	0:02	0:02	0:02	0:00	0:02
B744	31,000	0:00	0:03	0:07	0:03	0:04	0:07
Total delay of 3 flights					0:05	0:04	0:09

Table 5. Physical and aerodynamic characteristics of the B744.

Physical characteristics:	
Take-off weight	362,880 kg
Wing area	524.90 m^2
Aerodynamic characteristics (Cavcar and Cavcar, 2003)	
Parasite drag coefficient	0.0268
Induced drag coefficient	0.0432
Assumed values:	
Specific fuel consumption at sea level	0.75 kg-fuel/kg-thrust/hour

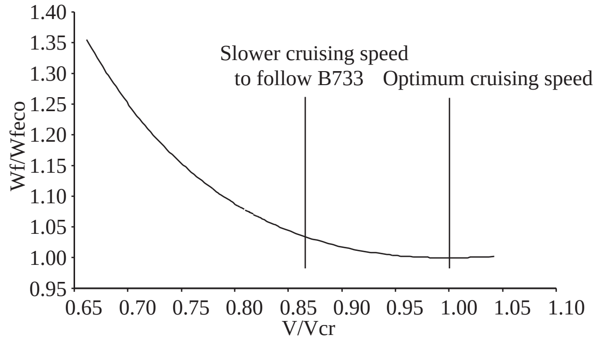

Figure 9. Variation of fuel consumption with the ratio of real flight speed to the optimum speed for B744 aircraft.

This analysis indicates that all the planes have to fly at their optimum cruising speeds and at their optimum flight altitudes, considering fuel costs. However, an aircraft can be constrained to fly at a slower speed on a given route in order to follow a lower performance leading aircraft without compromising safety. Otherwise, the following aircraft will have to be delayed on the ground, which is less costly and safer.

Conclusion

Aircraft performance differences cause air traffic delays. Lower performance aircraft determine airspace capacity by constraining the performances of other aircraft within the system. In addition to air traffic delays, lower performance aircraft may cause excessive fuel consumption on other flights. Since different types of aircraft are designed for different mission objectives and economic targets, it is impossible to eliminate performance differences. However, the effect of performance differences can be reduced by other means.

Flow management units can take performance differences into account and assign departure priority to higher performance aircraft. Special attention must be paid in assigning similar performance aircraft to the same flight altitudes on the same route. Although there is a natural separation between propeller aircraft and turbojet/fan aircraft for en route conditions due to high altitude limitations of propeller aircraft, new airspace classifications can be implemented for different aircraft performance categories by the allocation of higher flight altitudes to higher performance aircraft.

Aviation authorities should consider implementing some additional performance requirements in airworthiness standards. Minimum performance requirements for climbing and cruising conditions and their variations by altitude can be established for each aircraft category.

Although a deterministic proof is presented in this paper, a complex simulation analysis based on real traffic and airspace data should be conducted in order to measure the impact of aircraft performance differences on air traffic delays in real traffic conditions.

Symbols

c_T	thrust specific fuel consumption
c_P	power specific fuel consumption
C_{D_0}	parasite drag coefficient
D	drag force
E_m	maximum lift to drag ratio
g	acceleration due to gravity
h	flight altitude
H_{CR}	cruise altitude
i	$i = \{1,2,3, \ldots, n\}$ flight index
k	induced drag coefficient
P	engine shaft power
S	wing area of the aircraft
s	longitudinal separation distance
s_v	vertical separation distance
T	thrust
R	range
t	time
t_{cl}	climb time to the cruise altitude
t_0	departure estimated time
t_p	delay time due to performance differences
t_R	real departure time
V	airspeed
V_{cr}	optimum cruise speed
v	rate of climb
W	weight of aircraft
W_f	weight of fuel
W_{feco}	weight of fuel with optimum cruise speed
x	horizontal distance from any reference point
x_{cl}	horizontal distance to climb to the cruise altitude
η	propeller efficiency
ρ	air density
σ	relative air density
τ	real time

Abbreviations

A340	Airbus A340-200
ATC	Air Traffic Control
ATM	Air Traffic Management
BADA	Base of Aircraft Data
B733	Boeing 737-300
B744	Boeing 747-400
BA46	British Aerospace 146-100/200/300, RJ Series
CNS	Communication, Navigation and Surveillance
C160	C-160 Transall
C550	Cessna Citation II-S2
DH8C	De Havilland Dash 8-300
D328	Dornier 328
EUROCONTROL	The European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
F900	Falcon 900
GAO	United States General Accounting Office
ICAO	International Civil Aviation Organization
MD-11	Boeing (formerly McDonnell Douglas)
PA27	Piper Aztec
P28A	Piper Cherokee/Archer/Dakota/Warrior
PA34	Piper PA-34 Seneca
ROC	Rate of Climb
SB20	Saab 2000

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