



Airport Safety, Capacity and Investment

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Introduction

The title 'Airport Safety, Capacity and Investment' could potentially cover an enormous range of topics and approaches. Techniques used include probabilistic risk analysis, queueing theory, operational research, and cost benefit analysis (CBA). The aim here is both to give an impression of the whole subject and to focus on a few key topics. Surveillance technology plays an important part in delivering safety and capacity, but has to be seen in the larger system picture, particularly when investment is contemplated.

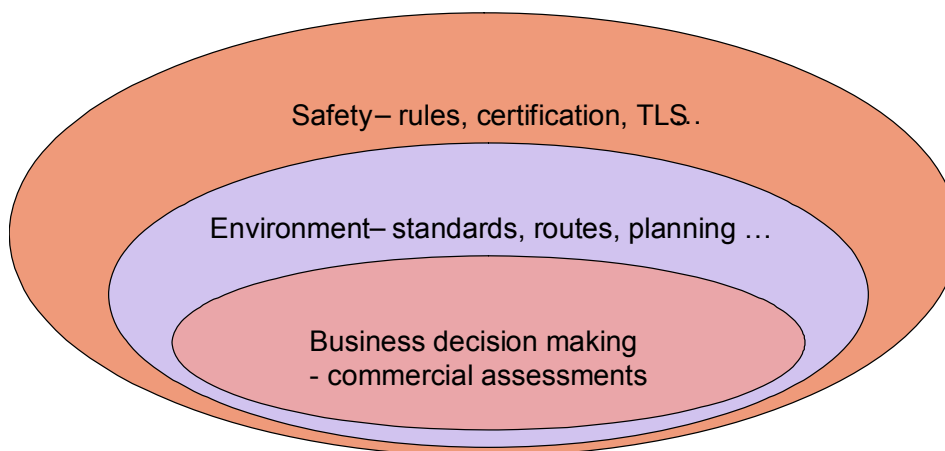


Figure 1. Airport ATC decision making

This first figure tries to show the context of airport air traffic control (ATC) business decision making, which now involves very commercial assessments. Safety, including rules, certification, and Target Levels of Safety, is paramount. Next – and assuming increasing importance – come Environment issues, such as standards, routes, and planning restrictions. Noise and pollutants, for instance nitrogen oxides, particulates and other emissions, are now of considerable concern to people living near airports. The crucial message here is that operational and technical decisions must be made in the context of proposals and options that are safe and environmentally sensible.

Safety

Safety is paramount. Many important safety-related factors and processes need consideration. An initial list might be:

- Airborne radar separation
- Wake vortex separations
 - WV Advisory systems
- Runway occupancy time for arrivals and departures
 - Aircraft speeds, layout
- Controller workload
- Equipment protection zones (eg ILS, MLS)
- Runway incursions and surface incidents
 - Reporting systems
- Equipment failures
- Human errors
- Weather (wind, visibility)
 - CAT I, II and III capacity

Which of these have technological solutions? Wake vortex advisory systems have been researched for many years, the basic idea being that reasonably high winds blow away aircraft vortices so that they do not affect a following aircraft – there is some interesting current work. The poor weather capacity of major airports is a reason for buying systems such as MLS, which have smaller protection zones near to runways than ILS, and so enable more traffic. Much more attention is now being paid to runway incursions.

Airport safety assessment presents a rather mixed picture. This list is a personal view, but likely to be widely shared by safety professionals.

- No 'Safety and Capacity Trade-offs': acceptable safety must be achieved
- Wake vortex separations were created about 30 years ago – they are believed to be generally very cautious
- Formal safety management processes, increasingly based on Safety Cases
- Few validated quantitative risk assessment models – ratio of incidents to accidents difficult to estimate
- Incident monitoring strong in some States but not generally
- 'Political' responses following accidents

The Safety Case philosophy has been very popular in the UK. Essentially, the operator has to demonstrate to the safety regulator that potential hazards have been examined, that equipment is 'fit for purpose', and that appropriate defensive mechanisms and reversionary operating modes are in place. Risk assessments can be very difficult for airport operations because of the complex environment and possible failure modes.

Wake vortices are a major part of the 'safety environment'. They have huge implications for safety and capacity. They were introduced when 'jumbo jets' started to operate. The roll effects of a wake vortex can be severe, so the separations between aircraft are set cautiously.

Leading aircraft (– examples)	Following Aircraft	Minimum Distance – nautical miles
Heavy – B747, B767, Airbus A330	Heavy	4
	Medium	5
	Small	6
	Light	8
Medium – B737, Airbus A320	Medium	3
	Small	4
	Light	6
Small – EMB-135, F28,	Medium or Small	3
	Light	4
Light – SD3-60	None	-

Figure 2. Wake Vortex Minima – arrivals (UK)

The above Figure shows the UK's Wake Vortex Minima for arrivals. These are slightly different from the ICAO version; the departures minima are time-based and more complex. These large distances affect capacity considerably, and lead to the need to sequence aircraft so as to avoid having to use the largest separations.

Linkages

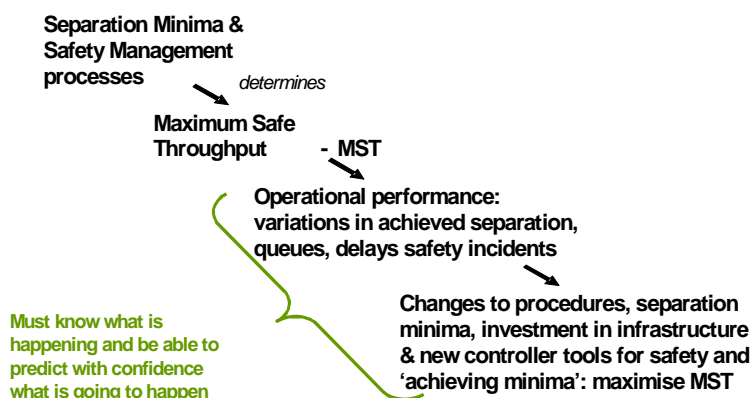


Figure 3. Safety, Capacity, Operations and Investment linkages

There are linkages between safety, capacity, operations and investment. Figure 3 illustrates some of these. The phrase Maximum Safe Throughput – MST – is used here, although queueing theorists would call it Service Rate. MST emphasizes the linkage to safe operations. The comment at the left hand side is a general one, but obviously has special relevance to surveillance and detection.

Capacity

Capacity problems are not new:

"The increase in the volume of traffic had brought about increased congestion around major airports."

"The problem of ATC as regards the expeditious handling of traffic thus resolves itself into finding techniques which "waste" no more time than is strictly necessary and, if possible, "waste" that time in the most economical manner."

These quotes are from a paper by G. E. Bell in 1949 (Journal of the Royal Aeronautical Society 1949, 53, 965). At that time (1948), the average airport congestion delay at London Airport was 2 minutes for takeoffs and 3.5 minutes for landings.

For airport delays, there is only one Queueing Theory graph that really matters – Figure 4.

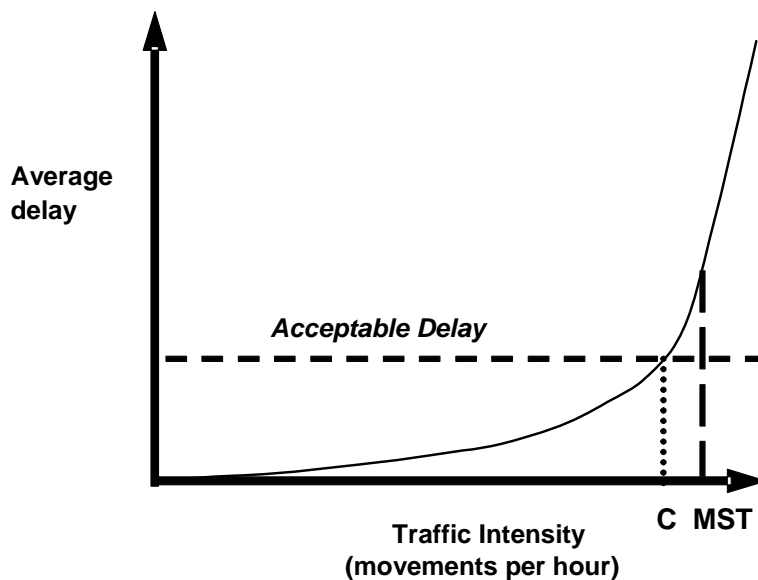


Figure 4. Average delay versus traffic intensity – the capacity C is slightly less than the Maximum Safe Throughput, MST.

Figure 4 illustrates that there needs to be an 'acceptable delay' target between the airlines, airport operator (mainly because of ramp and terminal congestion) and ATC. This fixes the scheduling capacity C at slightly less than the Maximum Safe Throughput, MST. Any higher traffic than C produces very large congestion delays.

The value of MST is crucial. What determines its value? The Appendix sets out and analyses a very simple model for an Arrival – Departure – Arrival operation “A-D-A”, a typical busy mixed mode runway. Some key features are summarised here. The basic sequence is something like:

1. Arrival crosses threshold and lands
2. Departure lines up behind the arrival
3. When arrival is clear of runway the departure roll begins
4. Departure becomes airborne
5. “Safety buffer time” of some seconds before next arrival crosses threshold

ATC must set up an inter-arrival separation that “guarantees” that departures can be interleaved between arrival pairs. Some critical component timings are:

- AO - arrival runway occupancy
- DO - departure occupancy (roll to airborne)
- SB - safety buffer
- σ - standard deviation of inter-arrival times
- T - inter-arrival spacing

Working through the sequence, the controllers have to plan to set up an average inter-arrival spacing of:

$$T = AO + DO + SB + (k \times \sigma)$$

In this equation, k is an observed constant for the airport in question, eg depending on the kinds of aircraft using the runway and ATC safety management practices. To minimise T, ie to save valuable seconds and hence increase the MST, the parameters in this equation have to be safely reduced, through operational changes and by using improvements generated through navigation, communication and surveillance. Is the investment worthwhile?

Investment Assessment

The value of investments can be assessed by a variety of financial techniques. One of the most popular is ‘Net Present Value’ – NPV. NPV discounts money flows in the future. Note that the focus is on cash not accounting. A discount rate of r % implies that £1 in n years time is worth $\frac{£1}{(1+r)^n}$ today. NPV is calculated by:

$$NPV = \sum (B_i - D_i - C_i) / (1+r)^i$$

where

B_i = Benefits in year i

D_i = Disbenefits in year i

C_i = Costs in year i

and the summation is over years 0 to n

If the NPV is positive then the decision to invest is supported.

An older and simpler technique is 'Payback'. This is the time it takes to generate sufficient *incremental* cash to recover initial *incremental* capital outlay in full. Some airlines use payback – often requiring the time to be less than 2 years.

NPV has one 'unknown parameter' – the discount rate of r %. One idea is that a (minimum) estimate for r is the Weighted Average Cost of Capital (WACC), which focuses on how much it costs to borrow money in order to invest. WACC is defined by:

$$\text{WACC} = (R_d \times \text{DE} + R_e \times \text{EQ}) / (\text{DE} + \text{EQ})$$

Where:

R_d = Company borrowing rate

R_e = Shareholders' expected return on equity

DE = Debt

EQ = Equity

A textbook commercial example from a year or so ago uses: $R_d = 8\%$, $R_e = 15\%$ (12% market return to shareholders plus 3% for risk), and DE/EQ (the company's gearing) as 1.42 (ie debt @ 60%) implies a WACC of 10.9%. Given the changes in the economic climate and the present state of the aviation industry, these may no longer be appropriate,

Indeed, industry analysts sometimes use a Risk-adjusted Discount Rate - r^* . The argument is that a rather higher figure than WACC should be used for cash flows in the period of uncertainty – or perhaps a steadily increasing value of r ? This is because of the uncertainties intrinsic to ATM developments. In particular, ATC and airlines are adaptive and tend to find a succession of low-cost operational improvements, so that investment benefits can be overstated and deferred. There is no obvious recipe for working out what r^* should be – perhaps 5% higher than the normal rate should be used?

There a variety of elements that can be included in ATM costs and benefits/disbenefits, most especially:

- Safety ('Value of Human Life': statistical cost of each fatality – €3M?)
- ATC service charge and equipment/staff cost
- Disbenefits from non-optimal flightpaths
- Operating disbenefits from delays
- Passenger delay disbenefits
- Capacity benefits (additional flights)

Eurocontrol and the FAA publish a great deal of information on these on their web sites.

On delay costs:

- IATA recommends figures for the average cost of delay to aircraft operators:
 - €22 per minute on the ground, and
 - €33 per minute in the air.

- FAA recommends hourly values of travel time savings on air carriers (1998 \$):
 - \$19.50 for personal
 - \$34.50 for business

But passenger delay disbenefits are not always included in airport financial assessments. The problem is that a passenger time saving is not 'hard cash' to the airline or airport operator.

Another important gain is the so-called 'Value of a Flight': how much an airline would be prepared to pay to have an additional flight. This obviously only means something at constrained airports, where there is little available capacity at peak hours. The value depends critically on such factors as scarcity, time of day, complementary slots, linkages to other services, etc. Given few additional fixed costs, the value will relate to airline operating profit. A UK 1998 figure for an additional flight was €3000+ – but this was in a more profitable era for major airlines. Airline yields are much lower now – and increasing competition implies these may persist in 'normal' periods. Indirect estimates could be made from slot trading. Moreover, it has been noted that airlines are often "willing" to incur penalties of the order of €1500 per flight in respect of noise restrictions fines. A figure of €700 has been used in some Eurocontrol studies.

What does this all mean? An illustration – based loosely on some past 'future avionics' proposals – may help to provide some warnings. Figure 5 shows illustrative yearly cash flows (in real prices) for a major system change.

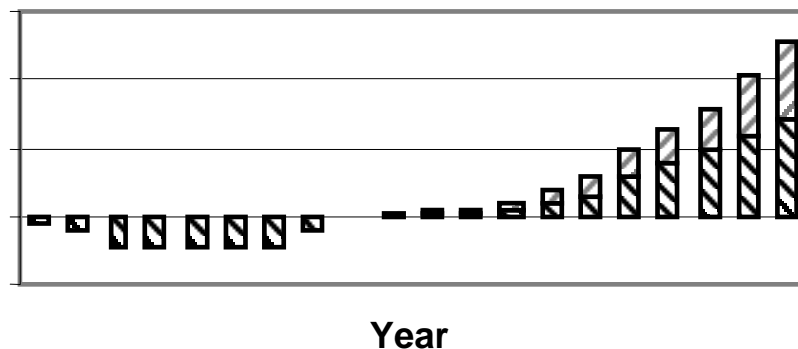


Figure 5. Cash Flows (real prices) for an illustrative major system change

This is a strategic change, with aircraft/ground re-equipment over a period of years. The roll out of kit involves no equipment retrofiting. There is next a 'bedding in' period, and then benefits in this example mainly derive from traffic growth. Some benefits are from passenger time savings – shown as the top part of the bars. With a discount rate of 10% the NPV is positive and hence worthwhile. However, this includes all the passenger time gains; if these are not counted, then the NPV is negative, ie the investment is not worthwhile.

Worse follows if a risk-adjusted discount rate r^* is applied to benefits, even if these include all the passenger time gains. With a rate of 15%, the result is Figure 6.

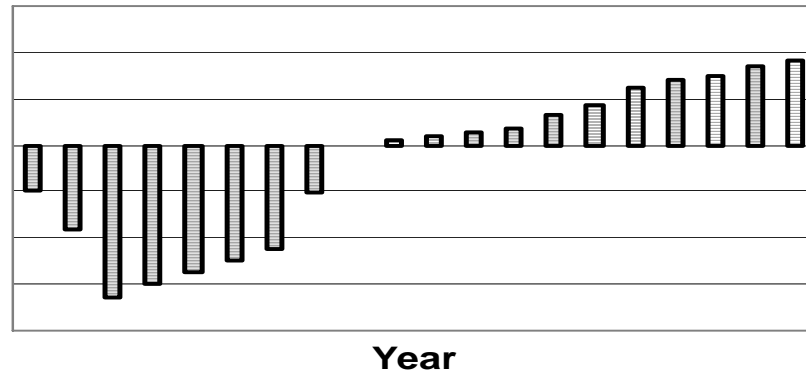


Figure 6. Cash flows (real prices) for an illustrative major ATM system change, with risk-adjusted discounting

The heavily discounted cash flows sum to a large negative figure. The costs are all 'up front', but the benefits are uncertain and take too long to arrive.

Conclusions – focused on Surveillance

Safe and efficient airport operations have been evolved over many years – the system is mature and the focus is on 'best practice'.

Capacity is well understood, but it requires continuous safety monitoring and assessment.

Many prima facie worthwhile improvements might be made. The problem is producing convincing cases in absolute safety terms and relative to competitor technologies.

Assessment problems include:

- Shortage of robust safety models (NB: there is a need to collect safety incident data rigorously across Europe)
- Operational adaptive skills of ATC and airlines, which tend to reduce/defer new technology benefits
- Few changes produce immediate operational (hard) cost savings to airlines and airports

CBA and payback are important but there is still a role for strategic leadership, particularly in safety and systems architecture.

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MAXIMUM SAFE THROUGHPUT OF A MIXED MODE RUNWAY: A SIMPLE MODEL

What sorts of changes in operations would be necessary to produce an increase in the Maximum Safe Throughput of a mixed mode runway? To discuss changes, it is first necessary to set out a simple model of mixed mode operations. The technological and operational modifications necessary to ensure such changes are not discussed here. Reality is more complex, of course, but the crucial features can be represented in a very simple way.

The basic airport operation assumed is of an alternation of arrivals and departures using the runway, with the following “A-D-A” sequence:

1. arrival crosses threshold and lands.
2. departure lines up behind the arrival.
3. when arrival is clear of runway the departure roll begins.
4. departure becomes airborne.
5. “safety buffer time” of some seconds before next arrival crosses threshold.

This is the base sequence observed at busy airports when arrivals and departures are about equal in number. It is “perturbed” by instances of two or more departures or two or more arrivals when there are queues of departures – or when flow-managed departure slots have to take priority – and arrivals respectively. There are also additional constraints on both departure (eg slow aircraft followed by fast aircraft on same route) and arrival (eg Heavy aircraft followed by Light aircraft) sequences.

The A-D-A sequence can only function in a sustained fashion if ATC set up an inter-arrival separation that offers a “guarantee” that departures can be interleaved between arrival pairs. This implies the need to focus on the following critical ‘average’ component timings:

- AO - arrival runway occupancy time
- DO - departure occupancy (roll to airborne) time
- SB - safety buffer
- σ - standard deviation of inter-arrival times (used to measure the amount that the observed times are spread about the average)
- T - inter-arrival spacing

To accomplish a departure between two arrivals the controller must plan to set up an average inter-arrival spacing of:

$$T = AO + DO + SB + (k \times \sigma)$$

Each second in T is very valuable in capacity terms. Note it is assumed here that it is the arrival occupancy which is critical, not the departure line-up time – but this may not always be the case. k is a constant which expresses the fact that the controller cannot simply assume that it is only the average times that matter. If an inter-arrival spacing is markedly less than the average – perhaps because the following aircraft did not decelerate as much as usual from the initial approach fix – then the departure might well not be allowed to leave the holding area if it were to be believed that the safety buffer had been “eaten away”. In normal circumstances, the controllers cannot allow two aircraft to be actively using the runway at the same time. Nor can they operate with a much higher “go around” rate than is considered acceptable by safety managers.

The controllers setting up the arrival sequence thus have to ensure that the variability in inter-arrival spacing at threshold – which, it must be stressed, is dependent on how the pilots of the aircraft concerned fly in from the initial approach fix as well as how accurately the controller sets up the initial spacing – is catered for. In the algebraic expression, this is allowed for by adding the term proportional to the standard deviation of the inter-arrival spacing. A fit to the data would probably produce a value for k of the order of 1½. Controllers do not of course actually carry out computations of statistical distributions. The term $k \times \sigma$ just represents in broad terms the product of their experience and intuition.

The values of all the parameters must be carefully monitored as part of the safety management process. If, for example, the actual value of SB is allowed to reduce or the inter-arrival standard deviation σ is allowed to increase, then there would need to be concerted action to assure safety.

There are also, of course, variations in arrival occupancy AO and departure occupancy DO, but “bits” of their standard deviations have not been added here because in terms of statistical variation they would probably not be as important as the inter-arrival time variability. Effectively, the allowance for such variations is subsumed in the safety buffer, SB. It would be conceptually straightforward to add in such elements to the “ σ ” term if a fuller model were to be required – but it would not be straightforward to validate fully such a model. This would be necessary if the model were to be required to represent separations under more complex control procedures, eg “tailored” inter-arrival times.

The inter-arrival time determines MST: the smaller the value of T the larger the value of MST, which equals $(2 \times 3600/T)$. Maximizing MST thus translates into minimizing T, and hence into minimizing the component timings which constitute T. Operational aspects of these components are discussed in turn.

AO - arrival runway occupancy time: Assume that this is the critical factor rather than lining-up time, ie that the latter will be accomplished before the landing aircraft is clear of the runway. The incidence of unnecessarily long times for this part of the operation can be reduced in a number of ways by using ATC instructions which expedite the operation, increasing the number of runway exits, or making these exits of “rapid turn-off” form.

DO - departure roll to airborne time: Again, the ATC instructions used need to be of a form that will ensure expedition. The aircraft’s roll to airborne time on the runway is governed by the flight operations requirements for a safe manoeuvre, and is virtually fixed given full power acceleration. However, the time interval of interest starts with the ATC instruction for clearance to roll, which can sometimes be improved.

SB - safety buffer: The safety buffer – the time between a departure's airborne time and the next arrival crossing the threshold – has always been recognized as a crucial parameter in the assessment of capacity. The need for this safety separation critically affects the decisions made by the controller when considering whether or not it would be prudent to release a departure from the holding point. The value used for the safety buffer will depend on such things as the nature of recommended operational practices in the prevailing weather conditions, radar and other equipment available to the controller, and the performance of the aircraft involved (it may be, for example, that aircraft using Flight Management Systems are more likely to maintain spacings). A value of about 30 seconds might be appropriate for the safety buffer, ie is seen as ensuring the necessary degree of safety: this corresponds to a distance from threshold of about 1 nautical mile.

σ - standard deviation of inter-arrival spacing: The standard deviation is multiplied by a factor k , which essentially sets the balance between too many go-arounds or occasions when the controller does not attempt to insert a departure (k small) and an inefficient operation having unnecessarily long inter-arrival separations (k large). The controllers' instructions set up the initial separations, which are then changed by the actions of the pilots when they decelerate the aircraft in the final approach.

To reduce the standard deviation, it is therefore necessary to focus on the controllers' instructions, perhaps examining what could be gained from computer assistance, and/or on the piloting of the aircraft, perhaps by requiring particular operating procedures. It should be emphasized again that the variability due to pilot effects is additional to that from ATC procedures. The "minimum" inter-arrival spacing varies between airports: for example, it may be more difficult for controllers to set up separations in circumstances where there is a 90-degree heading change onto the final approach, as compared with a long and straight "run in".

It is also possible to reduce the average inter-arrival time T by setting up particular sequences of aircraft. The basic equation for T conceals some structure in this regard. The word "average" was not defined. With a random sequence of aircraft types in the arrival and departure traffic streams, the correct "average" that the controller would use would need to be somewhat larger than the arithmetic means. This is because the controller who is planning arrival separations may not actually know the type of departure to expect and thus has to allow for the fact that on occasion there could be a sequence of Heavy category aircraft, with their markedly longer runway occupancy times.

To reduce the average inter-arrival time, it is therefore potentially possible to "tailor" the inter-arrival separations to the types of aircraft in the runway sequence. It is easy to see how this could be done if the departure and arrival sequences could be wholly pre-specified, at least for 15/20 minutes in the future (ie to cover the stack-threshold segment within which the arrival sequence is set up). If, however, there were some degree of uncertainty in the sequence then such "clockwork" timings would not function perfectly. The critical question is how efficiently the operation would be likely to work in practice. It should be stressed that such tailoring has to take place during the setting-up of the arrival sequence if it is to produce a reduction in the average inter-arrival interval. Tactical changes to the aircraft spacings during the final approach, say, to adjust for a Light or Heavy departure, while they will add to safety or reduce the chance of a go-around, do not change the average inter-arrival spacing. Tailoring would require a more complex model to account for (eg) the different combinations of aircraft categories in an arrival/departure sequence and the variations in arrival and departure occupancies.

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