QUANTIFYING AIRLINE DELAY COSTS
– THE BALANCE BETWEEN STRATEGIC AND TACTICAL COSTS


Dr Andrew Cook, Principal Research Fellow, Department of Transport Studies,
University of Westminster, 35 Marylebone Road, London, United Kingdom, NW1 5LS
Tel: +44 (0)20 7911 5801, Fax: +44 (0)20 7911 5057, E-mail: cookaj@westminster.ac.uk

Graham Tanner, Research Fellow, Department of Transport Studies,
University of Westminster, London, United Kingdom

Philippe Enaud, Senior Operational Expert, Performance Review Unit,
EUROCONTROL, Brussels, Belgium

Abstract

Airline delay costs are incurred both on the day of operations (tactical cost) and at the planning stage (strategic cost). The latter may take the form of buffer in schedules. Strategic and tactical costs are not independent. Passenger costs of delay to the airline, crew, fuel, maintenance and fleet costs are quantified. Cost trade-offs are presented as a 3D plot assessing the ‘break-even’ point for schedule buffer as a percentage of flights experiencing tactical delay reductions. Optimum schedule buffers are explored in the critical context of delay predictability and airline economics. Passenger ‘hard’ costs dominate the tactical savings.

Keywords: cost of delay, airline, tactical delay, schedule buffer.

1 Introduction

Delay costs severely affect airline profitability. These are incurred both on the day of operations (tactical cost) and also at the planning stage (strategic cost). The latter takes the form of contingencies for dealing with the impact of tactical delay, such as buffer in schedules. This paper critically examines the cost trade-off between putting buffer into schedules and the risk of allowing tactical delay to disrupt operations. Per-minute strategic costs are typically rather lower than per-minute tactical costs, although they are largely inescapable once committed to in the schedule.

Extensive tabulations and the derivation of the strategic and tactical costs used in this paper are presented in a reference document for European airline delay costs (Cook and Tanner, 2010), which is an update and extension of previous work establishing these costs for 2002-3. The new reference document takes into account, as far as possible, relevant changes in the economic and regulatory environment since the 2002-3 values
were derived, in addition to enhancing aspects of the methodology. Whilst this paper briefly summarises the key features of these costs, the focus is on the trade-off between the strategic investment in buffers and the risk of incurring tactical costs.

The cost elements quantified are: passenger costs of delay to the airline, crew, fuel, maintenance and fleet costs. They have each been calculated for four operational phases: at-gate, taxi, en-route (cruise/route extension) and arrival management (e.g. flow sequencing, stacking). The values have also been estimated under three cost scenarios: ‘low’, ‘base’ and ‘high’. These scenarios are designed to cover the likely range of costs for European operators, and each one has particular aircraft seat capacities and load factors assigned. Across all cost elements, the ‘base’ cost scenario is, to the greatest extent possible, designed to reflect the typical case. The calculations are undertaken for twelve aircraft types, with the B737-800 selected for illustration in this paper.

The strategic cost calculations aim to capture the additional costs of resources (such as aircraft and crew) resulting from increased schedule time. As an approximation, some of the calculations assume that the number of cycles is fixed at the point that the strategic cost is evaluated. For example, the timetable has already been determined in terms of the number of rotations for a particular city-pair on a given day and season but the amount of buffer in the schedule is yet to be decided.

On the day of operations, original delays caused by one aircraft (‘primary’ delays) cause ‘knock-on’ effects in the rest of the network (known as ‘secondary’ or ‘reactionary’ delays). In our full reporting (Cook and Tanner, 2010) a detailed account is given of reactionary delay costs. Reactionary delay is treated as at-gate delay and the calculations take into account the magnitude of the primary delay (larger primary delays tend to cause more reactionary delay). Caps are applied at costs comparable with the cost of cancelling a flight. At lower delay, recoveries between rotations are accounted for: these are largely made through schedule buffer and slack time (see Section 3.1) at-gate, and sometimes by achieving a faster turnaround at the gate.

![Fig. 1. Cost elements by delay level](image-url)
Fig. 1 shows which cost of delay elements need to be considered at each level. Key facets of these cost models are summarised in Section 2. No passenger delay costs are considered at the strategic level. Although some contingency for passenger delay is invested in operations at the strategic phase, for example having additional staff at airports to manage them, these costs are, as an approximation, assumed not to vary as a function of anticipated delay and are thus strategically treated as zero and assigned wholly to the tactical phase. It is important to note that strategic costs and tactical costs are not independent: reactionary delay magnitudes depend on the airline’s ability to recover from the delay, due to the amount of schedule buffer, for example. If no buffers were used, the reactionary costs would increase markedly and the total tactical costs would thus be significantly higher. It is to be borne in mind that the calculations are thus based on the current equilibrium of typical European operations. Whilst reactionary costs are not part of the trade-off calculations in this paper, we discuss such implications and how this might be developed further in future research.

2 Method

In this section, key facets of the cost models are presented. More detail is dedicated to the passenger costs, as these often dominate the overall cost of delay to an airline and we will later see how the shape of the cost curve for passenger ‘hard’ costs influences the trade-off between schedule buffers and tactical delay.

2.1 Non-passenger costs of delay to the airline

**Fuel.** The at-gate calculations assume the engines and Auxiliary Power Unit are off. Cruise fuel burn assumes average fuel flow in typical cruise with a 65% load factor, as calculated by Lufthansa Systems (using the application now known as ‘Lido/Flight’). Into-plane costs of fuel (Jet A1) are sourced from ‘Rotterdam’ (Amsterdam-Rotterdam-Antwerp) spot prices (Energy Information Administration, 2010). The cost of fuel since 2003 has approximately doubled: our base cost value for 2010 is €0.60 per kg.

**Maintenance.** Maintenance costs of delay incurred by aircraft relate to factors such as the mechanical attrition of aircraft waiting at gates (strategically or tactically) or aircraft accepting longer re-routes in order to obtain a better departure slot (tactically). The costs are based on values previously modelled in 2002, derived largely from interviews with eight European airlines, then updated to 2008 values using ICAO data. Our analyses of ICAO data (ICAO, 2008) have shown that the average European cost did not change from 2002 to 2008. ICAO data beyond 2008 were not available at the time of these calculations. Looking at limited, recently available financial returns from European airlines gives some insight into more recent changes. A small increase (5%) was applied to produce 2010 costs. For the tactical values, we derived marginal, time-based costs from unit costs. Overheads were first removed and then a gate-to-gate model used to apportion the maintenance cost between the airframe/components and powerplants across flight phases.
**Fleet.** Fleet costs refer to the full cost of fleet financing, such as depreciation, rentals and leases of flight equipment. These costs are determined by service hours. Since utilisation has only a very small effect on these costs, they are wholly allocated to the strategic phase and the corresponding tactical delay costs are thus taken to be zero. Costs are based on values previously modelled in 2002, sourced from airline interviews, literature and Airclaims data, then updated to 2008 values using ICAO data (ICAO, 2008). Our analysis showed that the average European cost fell by 15% from 2002 to 2008, although for several large European airlines they fell by 50%, with further (smaller) falls expected from 2008 to 2010 (UBM Aviation, 2008, 2010). The 2010 base scenario values are 20 – 35% lower than the 2002 values.

**Crew.** A detailed examination has been undertaken (University of Westminster, 2008) of payment mechanisms for aircraft crew (Nissen and Haase, 2006). Typical pilot and flight attendant salaries have been calculated for various European airlines, using their corresponding payment schemes with realistic annual block/flight duty hours, sectors flown and overnight stopovers. In Europe, airlines typically pay crew fixed salaries, supplemented by flying-time payments. Following the principle of fixed cycles, cycles-based sector pay and allowances were first subtracted from the annual, total cost estimates such that the remaining proportion of the salary assigned to the airline cost of using crew time is more accurately time-based. Airline on-costs (Doganis, 2005) are included and overtime is also considered.

### 2.2 Passenger costs of delay to the airline

Our methodology addresses airline delay costs – not wider costs of delay, which may be applicable in contexts such as the full societal impact of delay. Whilst passenger ‘value of time’ is an important consideration in wider transport economics, costs which do not impact on the airline’s business are not included in our calculations.

A cost of passenger delay to the airline may be classified as either a ‘hard’ or ‘soft’ cost. ‘Hard’ costs are due to such factors as passenger rebooking, compensation and care. Although potentially difficult to ascribe to a given flight due to accounting complications, these are, in theory at least, identifiable deficits in the airline’s bottom line.

‘Soft’ costs manifest themselves in several ways. Due to a delay on one occasion, a passenger may defect from an unpunctual airline as a result of dissatisfaction (and maybe later come back). A passenger with a flexible ticket may arrive at an airport and decide to take a competitor’s on-time flight instead of a delayed flight, on which they were originally booked. ‘Soft’ costs, exemplified by these types of revenue loss, are rather more difficult to quantify.

Since our earlier work in this area, with estimates derived from two European airlines’ data for 2003, the European Union’s air passenger compensation and assistance scheme (Regulation (EC) No 261/2004) has been introduced. It affords passengers with
additional rights in cases of flight disruption (denied boarding, cancellation and delay). Updates we have made to the 2003 values estimate these cost effects.

There is very little literature on actual passenger hard costs. Discussing disruption management, Kohl et al. (2007) do not quote specific delay costs. Bratu and Barnhart (2006) use values of time to estimate passenger costs. Jovanović (2008) appears to be the only publication to date specifically estimating the cost impact of Regulation 261, citing a comprehensive response from a major European, full-service, network carrier, and more limited data from another, similar carrier.

Longer passenger delays will tend to have higher per-minute costs than shorter ones. In order to distribute the hard costs as a function of delay duration, an empirical (airline) source (Jovanović, 2008) of ‘care’ costs (meal vouchers, hotel accommodation, tax-free vouchers, frequent-flyer programme miles and phonecards) was combined (Cook et al., 2009) with a theoretical distribution of ‘reaccommodation’ costs (rerouting/rebooking passengers, ticket reimbursements and compensation). Good power curve \( y = px^q \) fits (Cook and Tanner, 2010) of these costs are shown in Fig. 2 for the three cost scenarios. These costs are per-passenger: under each scenario, typical seat capacities and load factors are used to translate these costs into per-aircraft costs.

![Fig. 2. Power curve fit of passenger hard costs as a function of delay duration](image)

Since soft costs refer to a loss in revenue to one airline as a result of a delay on one occasion, this loss may be considered to be largely the gain of another airline, gaining a passenger who has transferred their custom. When scalable costs (multiplied over a period of time or a network) are assessed, only some net loss to the airlines of the soft costs is likely (e.g. due to trip mode substitution, trip consolidation, trip replacement (e.g. teleconference) or cancellation). As the calculations of this paper refer to schedule buffer trade-offs for a whole season, 10% of the full soft costs estimated (Cook and Tanner, 2010) are used. Airlines may assess this differently for specific rotations, such as high-yield feeder flights. This remains an issue for future research.
These costs have complex interdependencies. For example, the more buffer in an airline’s schedule, the more punctual its operations are likely to be, and the lower the soft costs. Lower soft costs are also likely to result from a generous airline policy regarding compensation and care as a result of tactical delay – at the expense of higher hard costs. Overall, the aggregate, total passenger base cost scenario for 2010 (with full soft costs) is 22% higher than the earlier, 2003 value. Inflation and the impact of Regulation 261 are incrementing factors, whilst increasingly cost-driven markets are suggested to have capped soft costs.

3 Calculation

This section first considers a simplified example of fixed inbound delay, before extending the calculations to variable inbound delay. The fixed example illustrates the basic economic principles of the trade-off between schedule buffer costs and tactical delay costs. The context of variable delay, introduced using calculus, stresses the importance of predictability.

3.1 Fixed inbound delay

The scheduled case in Fig. 3 shows a flight due to arrive at 1600, which takes 60 minutes to actively turnaround (e.g. deboard passengers, clean and refuel the aircraft, board new passengers). For simplicity, this example uses a fixed active turnaround time of 60 minutes, with no cost implications if it occurs later than planned. It is therefore cost-neutral, in this respect, to allow us to focus on the effect of adding buffer to the schedule.

A buffer of 30 minutes is added to the total at-gate time planned to give a scheduled departure time of 1730. This may be an entirely unconstrained choice of the airline, added purely as buffer in anticipation of particular inbound delays on this rotation, or it could be determined by other factors creating timetable slack, such as: waiting for other connecting inbound flights, the unavailability of an airport slot at 1700, or constraints at the next destination. In any case, it is fixed in advance in the schedule. It is thus a strategic cost.

![Fig. 3. Schedule buffer and tactical delay](image)
**Case A.** In tactical Case A, the inbound aircraft is 30 minutes late. With the fixed turnaround time, the aircraft thus leaves on time. The buffer has been used. Without the buffer, the aircraft would have been due to leave at 1700 and would have been 30 minutes late\(^1\). 30 minutes of new delay have thus been avoided by the presence of the buffer. Such costs avoided will be simply treated as primary delay, without any reactionary effect. This allows a transparent calculation, with a decoupling of the dependencies between the a priori strategic trade-off and the effect of (other) existing buffers. This implies that buffers elsewhere in the network at the strategic phase substantially mitigate reactionary effects (by design, at least).

**Case B.** For Case B, the buffer would not have been required on this occasion to absorb inbound delay, since there is none. However, the cost of the buffer is still consumed, since the strategic costs of having the aircraft in service and crew on duty (although see also Section 5.4) are fixed by the scheduled departure time of 1730.

### 3.2 Variable inbound delay

In deciding how much buffer to add to the schedule, a simple ‘equilibrium’ point may be defined, at which the additional cost \(dC_B\) of increasing the buffer further, equals the expected tactical cost \(dE(C_T)\) saved by the buffer:

\[
dC_B = -dE(C_T)
\]

(1)

The cost of the buffer \(C_B\) is fixed in advance and is known. The tactical cost is calculated as an ‘expected’ cost \(E(C_T)\) because it depends on the expected distribution, or predictability, of the delays.

Consider first the simple case where both the strategic and tactical costs are assumed to be proportional to the length of the delay. We define \(c_B\) and \(c_T\) as the cost per minute of strategic and tactical delay, respectively. As mentioned in Section 3.1, increasing the buffer by one minute increases the strategic cost of each flight by \(c_B\). Tactical cost savings, however, will only apply to flights with a delay \(t\) greater than the amount of buffer \(t_B\). Eq. (1) can be expressed as:

\[
c_B = c_T \cdot P(t > t_B)
\]

(2)

Suppose the cost of buffer to be \(c_B = € 15\) per minute and the tactical cost of delay to be \(€ 30\) per minute. In this simple example, an optimum situation pertains when the amount of buffer added is just large enough for 50% of the flights (the other 50% being punctual). This may be considered as a ‘break-even’ point for the investment of the buffer.

---

\(^1\) Without the buffer, there would be the equivalent of 30 minutes less strategic cost but 30 minutes additional tactical cost on the day of operations (under the simplified assumption of a fixed turnaround time).
The relationships of Eq. (1) and Eq. (2) may either be evaluated numerically (as in Section 4) or using calculus. In the latter case, we need to formalise these relationships in the context that tactical costs are not a linear function of the length of the delay, as has been demonstrated.

Firstly, it is necessary to define a probability density function $g(t)$ of the delayed flights (the subset for $t > t_B$). If $f(t)$ is the probability density function of $t$, such that

$$\int_{t_a}^{\infty} f(t) \, dt = P(t > t_B),$$

then:

$$g(t) = \frac{f(t)}{\int_{t_a}^{\infty} f(t) \, dt} = \frac{f(t)}{P(t > t_B)}$$

(where $\int_{t_a}^{\infty} g(t) \, dt = 1$)  \hspace{1cm} (3)

Whereas a function $C(t, t_B)$ for the tactical cost of delay is required (that is, the cost remaining after the buffer is added), a unit cost per minute $c_B$ will (still) suffice for the buffer, since this cost per minute does not vary as a function of the length of the delay. Consider an infinitesimal increase $dt_B$ in the amount of buffer $t_B$ added to a rotation: $t_B \rightarrow t_B + dt_B$. $dC(t, t_B)/dt_B$ expresses the rate of change of the tactical cost, by the buffer added. This can be expressed as an analogue of Eq. (1):

$$C_B \, dt_B = -\int_{t_a}^{\infty} dC(t, t_B) \cdot f(t) \, dt = -P(t > t_B) \int_{t_a}^{\infty} dC(t, t_B) \cdot g(t) \, dt$$

At equilibrium, a small increase in the cost of the buffer (left-hand side of equation) equals the marginal tactical cost (right-hand side) that is saved by adding the small amount of buffer $dt_B$. The integration is with respect to $dt$, not over $dt_B$, hence it is a marginal cost with respect to the buffer added; it also has to be weighted by the delay distribution given by $g(t)$.

Mindful of the limitations of the foregoing simplifications, they nevertheless allow transparent calculations to be made on the cost-benefit of adding buffer to schedules. In the next section we explore these cost trade-offs numerically, using a 3D plot of the break-even probabilities. Then, in the discussion of Section 5, we first investigate the key characteristics of the plot in a more operational context, before finally returning to Eq. (4) and evaluating it fully in this context.

4 Results

Buffer may be added to a schedule to reduce an inbound delay to a smaller outbound delay. The x-axis of Fig. 4 shows inbound delays; the y-axis shows outbound delays. The foreground to the right (the ‘floor’, in black) thus represents an area whereby the outbound delay is greater than the inbound delay, which is not of interest in terms of buffer calculations.
The longer base of the raised shape (running along the floor) represents the points where the inbound and outbound delay are equal \((t_B = 0)\). Behind this, the raised shape covers the area where the outbound delay is less than the inbound delay, that is, the inbound delay has been reduced by buffering \((t_B > 0)\). The height of the shape at each point (z-axis) is the percentage of flights experiencing this delay reduction, at which the tactical and strategic costs are equal – the break-even point.

As an example, the double-headed arrow (↕) represents an inbound delay of 120 minutes, with an outbound delay of zero minutes. This is an analogue of Case A. A 120-minute tactical delay costs €12 670 for a B737-800, whereas adding this much buffer to a schedule costs €1 790. The break-even point for adding this amount of buffer into the schedule is thus 14%. For every 100 flights, if 14 have inbound delays of 120 minutes, which is reduced by buffer to zero outbound delay, the tactical delay cost saved is 14 x 12 670 = €177k. The buffer is in place for all of these flights, including those with no delay (Case B analogue), at a total cost of €179k.

Towards the rear of the plot, on the right, small inbound delays have relatively low tactical costs, and thus ‘require’ a very high percentage of flights to be delayed in order to make the buffer cost effective. (Indeed, the plot is actually capped at 100%, whereby adding buffer to remove inbound delays of only several minutes would never be cost effective: they would require more than 100% of flights to be delayed to break even, which is clearly not possible).

It is, of course, not necessary to add as much buffer to a schedule that is anticipated to be large enough to reduce the inbound delay to zero. For example, the white marker on the surface of the shape corresponds to 30 minutes of added buffer, reducing an inbound delay of 60 minutes to an outbound delay of 30 minutes. This represents a tactical cost saving of €2 780 and is thus cost effective if it is made on at least 16% of occasions.
These initial observations on Fig. 4 illustrate how these types of calculations can be used to estimate the optimal amount of buffer to add to a schedule. We next examine these calculations more critically.

5 Discussion

In this section, various practicalities of the theories leading to Fig. 4 are discussed. Key assumptions underpinning these calculations are examined in terms of the changes to the results that would be expected if they were relaxed. Secondly, the basic contours of the shape in Fig. 4 are explored in terms of the associated economics. Finally, the operational context of current delays is discussed before we finalise the calculus.

5.1 Reactionary effects

The model presented excludes reactionary delay from the onward cost. If reactionary costs were included, the outbound costs would be higher, except for rather smaller delays, which are, on average, more easily recovered. With buffer costs unchanged, this would lower the surface of the plot, as the buffers would be cost effective at lower delay frequencies.

The a priori assumption was made in Section 3 that existing buffers successfully mitigate reactionary effects. For high levels of tactical delay this is not a strong assumption, as these will inevitably cause some reactionary effects on the day of operations. As will be examined next (Section 5.2), the most realistic scenarios are, in any case, for buffers which are neither very large nor very small.

5.2 Size of buffer

Buffers need to be large enough to absorb delays that are likely to have operational consequences. However, if too much buffer were added to any given turnaround, the total number of flights possible in the operational day would be reduced, and the fixed-rotation assumption of the model would be violated. This has complex implications for both the estimates of the tactical and strategic costs, in addition to the fact that it would become necessary to further include estimates for the value of a flight. EUROCONTROL (2009b) comments on the difficulty of quantifying the value of a flight, citing estimates of between € 700 and approximately € 10 000. Such estimates are rather volatile in the context of loss-making airlines and outside the context of an airline’s network (whereby the true value of a rotation can only be assessed in terms of its contribution to the full network).

A 120-minute tactical delay costs € 12 670 for a B737-800. For a given aircraft and cost scenario, the cost per minute of buffer is constant (approximately € 15 for B737-800), such that adding this amount of buffer to a schedule costs € 1 790. For comparison, the corresponding high cost scenario value is € 2 990. Contours of the shape in Fig. 4 are
discussed in the next section, although in the context of increased buffer costs, it is noted that for fixed tactical costs, if the cost of buffer were doubled, say, the surface contours remain exactly the same, whilst the height of each point would double. However, as has been remarked upon, these calculations are based on the current equilibrium of typical European operations and the tactical and strategic costs are not independent.

Turning to the United States, Ball et al. (2010) report on a study sponsored by the Federal Aviation Administration to estimate the total economic impact of flight delay in 2007. The cost of delay to airlines is estimated by modelling the relationship between airline total cost (as opposed to flight-by-flight) and operational performance metrics. Increases in operating costs to airlines due to tactical delay (“delay against schedule”) and strategic delay (as “schedule padding”) are calculated using statistical cost models with airline data. The costs of schedule buffer are estimated using less impeded block times and are similar to the tactical costs in magnitude, whereas, as discussed, our tactical costs are rather larger than our costs of schedule buffer. An equivalent plot of Fig. 4 using the data from Ball et al. (2010) would thus have a higher surface, as more tactical delay ‘savings’ would be required to ‘pay’ for the buffer.

The cross-sections of the shape nearest to the front of Fig. 4 represent the smallest reductions in onward delay reduction. For example, the nearest corner (front, left) represents an inbound delay of 120 minutes being reduced to an outbound delay of 119 minutes. Statistically, for the 121 passengers in the base scenario model for a B737-800, this represents an expected saving of €170, and is thus cost effective if this occurs for around 9% of flights. In practice, such small buffers would not actually be chosen, as their effects are likely to be insignificant within the unpredictabilities of taxi times and en-route weather, plus decisions to use accelerated fuel burn to recover delay. Small delays could almost always be recovered through a reduced turnaround time, in any case.

5.3 Cost contours

Further insights can be obtained into the economics of these trade-offs from the contours of the shape. Taking the long upper edge, in the foreground, from right to left, the slope is relatively steep at first, then flattens out somewhat. This is the ratio of the cost of the buffer required to reduce the inbound delay by one minute, to the corresponding tactical cost saving. As discussed, the strategic cost of buffer is linear as a function of delay duration and every buffer cost along this upper edge is approximately €15. The tactical costs quickly become dominated by the non-linear, hard passenger costs, which are estimated by a power curve (Fig. 2). For the left-hand side of the shape (inbound delay ≥ 60 minutes), the passenger hard costs represent some 75-90% of the tactical saving\(^2\). It is therefore unsurprising that this long upper surface is also very well modelled (\(r^2\): 0.97-0.99, across surface) by a power curve.

\(^2\) Calculation not shown. Whilst passenger costs dominate at-gate delays (and hence reactionary costs), fuel costs form the higher proportion of en-route delay costs at lower delay. This proportion gradually decreases. By 120 minutes, the en-route costs are strongly dominated by the passenger costs (from 80-90% across all twelve aircraft types).
The surface is everywhere lower in the foreground than at the rear, although this curvature is not as pronounced as that from left to right. Towards the front, the average saving per minute of the tactical delay reduction is higher, since these costs increase non-linearly as a function of the length of delay\(^3\). Towards the rear, the average tactical saving per minute is lower\(^4\) (because it is ‘diluted’ by lower savings). Since the cost per minute of buffer is constant, it is necessary to make the saving more often to break even towards the rear because the average benefit is less.

Tactical/strategic cost ratios are higher for widebodies. This means that lower break-even frequencies apply, such the height of the surface is lower for a widebody. For example, whereas the white marker in Fig. 4 for B737-800 has a break-even frequency of 16\%, for a B747-400 this value is 12\%.

5.4 *Passenger and crew costs*

This dominance of the passenger effects will persist as a good aggregate estimate of these costs, notwithstanding possible future refinements. The cost model currently allows for no interdependencies between flights for passenger costs, but uses average cost of delay estimates. However, some of the passengers onboard the inbound aircraft may be transferring onto other flights – their final delay at their destination might be less due to schedule buffering between such flights. (Less likely, other passengers onboard the inbound aircraft could even be on the next rotation of the same aircraft, which causes various complications for the calculation of both the primary delay and reactionary delay).

By treating the inbound and outbound costs as independent primary delay costs, different crew are assumed on the two rotations. More refined dependencies for crew costs between narrowbody rotations, incorporated elsewhere in the model (Cook and Tanner, 2010), are thus not included. (Exactly how this relative reduction in the crew cost is distributed between the inbound and outbound costs is not generally that critical, since the tactical costs are so strongly dominated by the passenger hard costs.) The net effect of including these dependencies would be to increase the break-even percentage, since the tactical saving is (slightly) less. Also, for rather large buffers, it would, in theory at least, more often be possible to optimise crew changes/allocations between rotations, such that the corresponding *strategic* costs could be reduced. This would be more difficult at outstations, where the crew slack time would thus more likely have an associated cost.

The extent to which these potential cost reductions would be off-set by the reactionary costs excluded from these exploratory calculations, is a subject for future research.

\(^3\) Reducing 120 minutes to 119 minutes saves €170, i.e. €170 per minute.
\(^4\) Reducing 120 minutes to 0 minutes saves €12 670, i.e. €106 per minute.
5.5 Predictability - average delay and specific delay

The frequency at which these delays are required in order for the investments in buffer to break even refer to specific rotations in an airline’s operations. Statistically expected delays, based on historical data, vary significantly from case to case. Airlines may wish to avoid the propagation of delays earlier in the day, which are more likely to have more severe reactionary effects throughout the rest of the operational day. They will also wish to avoid delay on rotations that have the greatest economic effect on the network as a whole, particularly an issue for hub-and-spoke operators. On the other hand, since schedule changes may have certain negative commercial impacts, such as a reduction in satisfying passenger demand, such pressures may encourage airlines to actually reduce schedule buffer in the morning peak and assign it to rotations in the middle of the day, when demand is lower.

European delay distribution data\textsuperscript{5} for 2009 may be considered both in general, for all delays, and, more specifically, for ‘slot’ (flow management\textsuperscript{6}) delays only. Fig. 5 shows the distribution of total European delay in 2009, as reported to EUROCONTROL by the airlines and collected through ACARS (Aircraft Communications, Addressing and Reporting System). 16.9\% of flights were exactly on time (a further 34.5\% were early), with the most common delay being in the 1-4 minutes range (11.3\%). Taking the upper end of the delays considered in this paper, only a very small proportion (1.04\%) were actually more than 120 minutes late in 2009. With respect to flow management delays, 92\% of flights in 2009 had no such delay, with a distribution (not shown) falling off even more sharply than that of Fig. 5. For example, only 0.04\% of (all) flights had slot delays of more than 120 minutes. The general trend in Europe is for delay variance to increase with average delay (Cook and Tanner, 2009), such that it might be reasonably expected that the spread of specific delay magnitudes experienced by airlines will increase with traffic volumes in future, underlining the fact that the operators are facing the economics of specific buffering decisions on specific rotations, rather than network averages.

\textsuperscript{5} Personal communication from EUROCONTROL Performance Review Unit (2010).
\textsuperscript{6} Usually referred to as an ‘ATFM (Air Traffic Flow Management) slot’.
5.6 Quantifying the variable delay

In Section 3.2, an initial treatment of variable tactical delay was established. Having explored these trade-offs further and set them in a more operational context, this discussion can be taken further. The total tactical delay cost for at-gate delay (summing the hard and soft passenger costs of delay to the airline, plus the crew and maintenance costs) may be approximated well ($r^2 > 0.99$; B737-800, $1 \leq t \leq 120$ minutes) by a simple quadratic $at + bt^2$. Since $(t - t_B)$ is the tactical delay remaining after the effect of the buffer, $C(t, t_B) = a(t - t_B) + b(t - t_B)^2$. Its derivative, introduced in Section 3.2, is:

$$dC(t, t_B)/dt_B = -a - 2b(t - t_B)$$

(5)

The expected value of $(t - t_B)$ is, by definition:

$$E(t - t_B) = \int_{t_B}^{\infty} (t - t_B) \cdot g(t)dt = \bar{t}_{t_{-t_B}}$$

(6)

where $\bar{t}_{t_{-t_B}}$ is the mean delay of delayed flights, remaining after the effect of the buffer (henceforth the subscript will be dropped). We are now in a position to evaluate Eq. (4). Substituting Eq. (5):

$$c_B dt_B = P(t > t_B) \int_{t_B}^{\infty} \{a + 2b(t - t_B)\}dt_B \cdot g(t)dt$$

(7)

Thus, with reference to Eq. (6) and recalling that the integral of $g(t)$ is unity (Eq. (3)):

$$c_B = P(t > t_B) \int_{t_B}^{\infty} \{a + 2b(t - t_B)\} \cdot g(t)dt = P(t > t_B) \cdot (a + 2b\bar{t})$$

(8)

For the B737-800, $c_B = 14.9$ (as used in Section 4), $a = 24.9$ and $b = 0.687$ (fit not shown). If the mean delay of the delayed flights ($\bar{t}$) after the effect of the buffer is 15 minutes, the cost equilibrium is reached at $P(t > t_B) = 33\%$. For the B747-400, $c_B = 29.7$ with $a = 59.1$, $b = 1.83$ ($r^2 > 0.99$; $1 \leq t \leq 120$ minutes, fit not shown). If $\bar{t}$ is (again) 15 minutes, the cost equilibrium for the B747-400 is reached at $P(t > t_B) = 26\%$. As expected, this equilibrium is reached at a lower delay threshold for the widebody, the ratio between these $P(t > t_B)$ values being very similar to that of the corresponding ratios for the white marker in Fig. 4, which was discussed under ‘Cost contours’ in Section 5.3. These delay levels are to be compared with the actual (average) delay distribution shown in Fig. 5; 48.6\% of flights overall are subject to tactical delay.

Eq. (8) results from the total tactical delay cost being modelled very well by a function of the form $at + bt^2$, which may, in fact, be reasonably approximated as $kr^2$. Future research should thus allow informative insights to be gained through exploring this delay cost expressed as a function of its mean (squared) and variance. Importantly, the variance term thus captures *predictability*, central to the discussion of both delay cost and schedule buffer. Predictability is functionally related to the former and informs rotation-specific decision-making in the case of adding buffer to schedules, as explored in Section 5.5.
6 Conclusions

Delay cost management usually focuses on the tactical phase, where a major challenge still facing the airline industry is the integration of (ground-based) disruption management techniques into flight planning. The quantification of the strategic costs of delay and the use of these costs to calculate the optimal amount of buffer to add to schedules has received less attention.

This paper has used estimations of tactical and strategic costs to quantify the trade-off between adding buffer to the schedule and the risk of incurring reactionary delay costs, in the critical context of expected delay frequencies and predictability. Whilst the cost estimates are based as far as possible on actual airline data, the opportunity remains to develop these models further, particularly in the decision-making and schedule-planning context of airline case studies. The limiting factor in such case studies is likely to be incomplete tactical cost of delay data, although our research in this field has allowed us to develop a detailed framework for collecting such data.

Evaluating the cost of passenger delay to the airlines represents a particular difficulty, especially soft costs, which can only be fully assessed through market research. Wider challenges in this area arise with regard to key performance indicators. Bratu and Barnhart (2004) show how passenger-centric metrics are superior to flight-based metrics for assessing passenger delays, primarily because the latter do not take account of replanned itineraries of passengers disrupted due to flight-leg cancellations and missed connections. These authors conclude that flight-leg delays severely underestimate passenger delays for hub-and-spoke airlines. Sherry et al. (2008) concur that “flight delay data is a poor proxy for measuring passenger trip delays”.

The main simplification made in these trade-off calculations is the exclusion of reactionary costs. Here, relatively little work has been undertaken and there remains an opportunity to extend such research into an operational context that specifically embraces the strategic trade-offs. These reactionary effects are dependent on a number of factors, such as time of day (primary delay typically causing greater reactionary delay when it occurs earlier in the day), the airline’s business and operational model (point-to-point or hub-and-spoke) and the airports served.

At the airport, schedule buffers may not always be entirely a matter of airline choice. They may be imposed, or made larger than desired, by airport slot constraints and thus be considered as a cost of congestion, albeit one which off-sets tactical delay costs. On the other hand, airports may be viewed as network nodes which multiply tactical delay. Schedule buffers and tactical delay are primary determinants of turnaround times and reactionary delay. Turnaround times are a key component of overall air traffic management (ATM) efficiency, with the majority of air transport delays originating from turnaround delays (EUROCONTROL, 2009a), that is, ground processes under local control outside the remit of ATM. Improving this is an important component of the Single European Sky ATM Research programme (SESAR) and of network performance: the associated tactical cost savings will include those of emissions charges from 2012.
Acknowledgements

The University of Westminster gratefully acknowledges the generous support of the European Organisation for the Safety of Air Navigation (EUROCONTROL) for enabling this research to be carried out. This paper has been cofinanced by EUROCONTROL under its Research Grant scheme. The content of the work does not necessarily reflect the official position of EUROCONTROL on the matter. © 2010, EUROCONTROL and the named authors. All Rights reserved.

References


