The challenge of managing airline delay costs

Dr Andrew Cook (Principal Research Fellow) and Graham Tanner (Research Fellow)*
Department of Transport Studies, University of Westminster, London

***Abstract*—Estimates of airline delay costs as a function of delay magnitude are combined with fuel and (future) emissions charges to make cost-benefit trade-offs in the pre-departure and airborne phases. Hypothetical scenarios for the distribution of flow management slots are explored in terms of their cost and target-setting implications. The general superiority of passenger-centric metrics is of significance for delay measurement, although *flight* delays are still the only commonly-reported type of metric in both the US and Europe. There is a particular need for further research into reactionary (network) effects, especially with regard to passenger metrics and flow management delay.**

***Index Terms*—cost of delay, disruption management, emissions, flow management, passenger.**

I. Introduction

A. Background and scope

In this paper we present estimates for the cost of delay to airlines, and show how these costs can be combined with fuel and (future) emissions charges to make cost-benefit trade-offs both in the pre-departure and airborne phases of delay cost management. We also examine some hypothetical scenarios for the distribution of Air Traffic Flow Management (ATFM) slots, exploring these in terms of their cost and target-setting implications.

The cost of delay to airline operations comprises several components. These include the costs of passenger delay to the airline, plus crew and maintenance costs. Also, primarily in the airborne phase, fuel costs need to considered, and, in the future, emissions charges. The total cost is often dominated by the passenger component. This component may be split into 'hard' costs, such as those due to passenger rebooking, compensation and care, and 'soft' costs. Hard costs are typically difficult to fully ascribe to a given flight due to accounting complications, but are, in theory at least, identifiable deficits in the airline's bottom line. Soft costs manifest themselves in several ways. Even with no experience of an airline, a passenger may perceive it to be unpunctual and choose another, instead. 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, but may even dominate the hard costs (Cramer and Irrgang (2007), Cook et al. (2004)). We summarise here our previous derivations of each of these cost components, focusing in particular on their *distribution* as a function of delay duration. For passenger delay, longer delays have higher associated costs per minute: hard costs are higher as airlines pay more in recovery and care costs, such as meal vouchers and overnight accommodation. The soft costs are also higher for longer delays, as passengers are more likely to be dissatisfied as the result of a longer delay than a shorter one. Although our models specify delay costs for each minute up to 300 minutes, and these explicit values are used in all calculations, selected mid-range values only are shown in tables, where applicable, to save space.

B. Delay management context

Airlines have windows of opportunity for mitigating against, and managing, delay costs, as illustrated in Table 1A and Table 1B.

TABLE 1A
DELAY COST MANAGEMENT BY PHASE OF FLIGHT (DESCRIPTIONS)

	Phase	Description
	Strategic	Resources committed at planning stage: advance delay contingencies
Tactical	Pre-departure	Slot management process. (Also decision point for fuel uplift.)
Tactical	Airborne	Speed/route adjustment; depends on: ATC, weather, fuel uplifted
Tactical	Post-flight	Aircraft, crew and passenger delay recovery

Disruption management is a vital component of airline operations[1]. It may focus on the ground-based recovery of operations, which have become misaligned from the strategic plan, and rarely extends to a properly costed recovery in the airborne phase. A major challenge facing the industry is the integration of disruption management techniques (and the supporting tools that are commercially available) into a *centralised* optimisation process, bringing together the various cost centres of an airline.

In particular, passenger services and reaccommodation (booking disrupted passengers onto new flights) are rarely integrated with flight operations. Kohl et al. (2007) comment that: "Successful operation of an airline depends on coordinated actions of all supporting functions.

* Corresponding author. Address: University of Westminster, 35 Marylebone Road, London, United Kingdom, NW1 5LS. E-mail address: cookaj@westminster.ac.uk (A. Cook).

[1] Substantial reviews of the literature are furnished by Bratu and Barnhart (2006) and by Kohl et al. (2007).

However, each group typically operates under its own directive, with its own budget and performance measures ... Generally, in the disruption management literature passengers are given a low priority".

TABLE 1B
DELAY COST MANAGEMENT BY PHASE OF FLIGHT (EXAMPLES)

	Phase	Example
	Strategic	Schedule buffers to absorb tactical delays, without over-compromising utilisation of aircraft/crew
Tactical	Pre-departure	Re-route: accepting/filing a longer route to bring a departure slot forward
Tactical	Airborne	Change of cost index[2]; request to ATC for change to filed plan
Tactical	Post-flight	Re-booking delayed passengers. (Potential of associated 'soft' costs.)

Narasimhan (2001) also offers a succinct summary of the challenge: "In most airlines … applications are not deeply integrated. This implies that two groups doing their individual best could actually be working against each other."

Although customer service coordinators are consulted, as Bratu and Barnhart (2006) comment, passenger disruptions rarely drive operational decision making. Aircraft and crew are often recovered first, with a need to respect aircraft maintenance requirements – especially for 'maintenance critical' aircraft (i.e. which will be grounded if not attended to). If a disruption management solution cannot be generated within a matter of minutes, it may become redundant, which still poses a serious problem for many optimisers.

C. *Overview of approach*

Costs have been calculated for each major cost of delay component. In each case, these are presented for each of twelve supported aircraft types, representing a range of equipment operated in Europe. The fundamental principle involved in calculating the maintenance and crew costs is to derive marginal, time-based costs from unit costs, by removing fixed costs and correctly apportioning cycles-based costs across marginal delay minutes. Whilst many delay costs differ by phase of flight, passenger costs are a notable exception, since these are only a function of arrival delay.

Costs are presented according to three cost scenarios: low, base and high. Scenario assumptions are consistent across all the cost models presented, for example with appropriate seat assumptions for different airline business models (e.g. aircraft class configurations) driving both the crew and passenger cost estimates.

[2] The cost index is a parameter set in the cockpit, which determines how the flight management system will control the aircraft. It quantifies the choice to fly faster to recover delay, or to fly slower to conserve fuel.

II. DELAYED PASSENGER COSTS

A. *Estimating hard and soft aggregate costs*

In previous papers we have detailed the calculation of passenger hard costs of delay to the airline (Cook et al., 2009) and the corresponding soft costs (Cook et al., 2009a). Base cost scenarios were derived from independently concurring sources (two European airlines) on total passenger costs for a 2003 reference base. Since then, however, a significant change has been brought about to both types of cost, by the European Union's air passenger compensation and assistance scheme (Regulation (EC) No 261/2004), introduced on 17 February 2005. It affords passengers with additional rights in cases of flight disruption (denied boarding, cancellation and delay) and only relates to departure delay; nothing is due to the passenger for any type of arrival delay or missed connection per se. It applies to any flight departing from the EU and to all flights operated by EU carriers from or to an EU airport.

In the context of disruption management, Kohl et al. (2007) do not quote specific delay costs, and 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.

The resulting aggregate cost estimations are summarised in Table 2. Two airline sources have been used to rationalise the equal (base scenario) split between hard and soft costs. The values set for the high and low cost estimates are more a matter of informed judgement, in particular subject to further research, but nonetheless based on semi-quantitative arguments. Soft costs, it is argued, are relatively less impacting for carriers with a low cost base, such that the ratio between the high and low scenarios is 4.0, although these are much closer for base and high scenarios. This asymmetry is intentional and reflects soft costs saturating out at higher total costs.

Overall, the total base cost scenario for 2008 is 20% higher than the 2003 value previously reported. Inflation and the impact of Regulation 261 have been cited as incrementing factors, whilst increasingly cost-driven markets have been cited as a capping effect through soft costs.

TABLE 2
THREE COST SCENARIOS FOR PASSENGER HARD AND SOFT COSTS

Cost type	Low	Base	High
Hard cost	0.11	0.18	0.22
Soft cost	0.05	0.18	0.20
Total	0.16	0.36	0.42

Costs are in Euros (2008) per average passenger, per average delay minute, per average delayed flight

B. Distributing the costs as a function of delay duration

Having derived the aggregate hard and soft passenger costs, it is now necessary to distribute these as a function of duration of delay: longer delays will tend to have higher per-minute costs than shorter ones.

Using large data sets for passenger booking and flight operations from a major US airline, 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, demonstrating that the average passenger delay is 1.7 times greater than the average flight-leg delay, with average disrupted passenger delay growing exponentially with load factors. Sherry et al. (2008) concur that "flight delay data is a poor proxy for measuring passenger trip delays". Based on a model using 2005 US data, they conclude that the average passenger trip delay is 34 minutes longer than the average flight delay (53 minutes). This suggests a factor of just over 1.6.

In order to distribute the hard costs as a function of delay duration, we combined an empirical (airline) source of 'care' costs (meal vouchers, hotel accommodation, tax-free vouchers, frequent-flyer programme miles and phonecards) with a theoretical distribution of 'reaccommodation' costs (rerouting/rebooking passengers, ticket reimbursements and compensation). Specifically-fitted, passenger-centric corrective weighting factors for the hard costs were used, with attention paid that neither care nor reaccommodation costs modelled were allowed to unduly dominate total values.

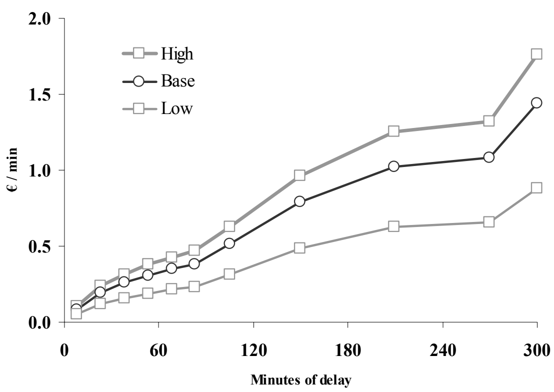

Fig. 1. Modelled distribution of (total) hard costs, for three scenarios.

For distributing the soft costs of delay, a logit function was used to express the propensity, 'Π', of a passenger switching from a given airline, to some other choice, after trips with given delay experiences (black curve, Fig. 2). Quantification of the saturation of delay inconvenience (primary survey, grey curve) and crossovers in Kano satisfaction factors[3] (primary analysis based on literature data; dashed vertical lines show boundary of intolerance) contributed towards the model. Relationships between market share, punctuality and customer satisfaction were also examined.

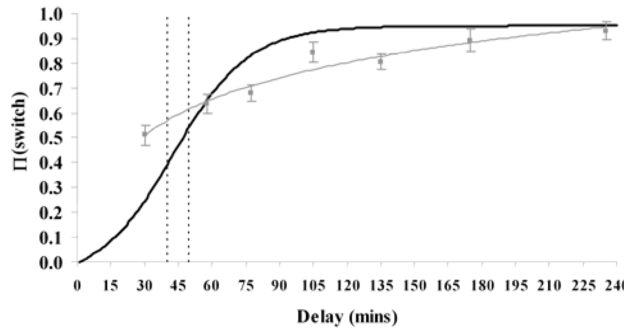

Fig. 2. Hypothesised switching propensity by delay duration

C. Per-aircraft passenger costs of delay

Table 3 shows some of the passenger cost of delay values translated into per-aircraft costs for each of the twelve supported aircraft types. Drawing on typical seat allocations, using ICAO 2006 fleet data with a sample of over 4000 aircraft, load factors of 60%, 75% and 90% were applied to the low, base and high cost scenarios, respectively, for narrowbodies (short haul). For widebodies (long haul), the load factor applied was 80%. In Table 3, mid-range values only are shown and only for the first three of the delay ranges modelled, to save space.

TABLE 3
PER-AIRCRAFT PASSENGER COSTS OF DELAY BY DELAY RANGE (BASE CASE SCENARIO)

Range:	1-15 mins	16-30 mins	31-45 mins
B737-300	12	35	60
B737-400	14	40	68
B737-500	11	31	53
B737-800	16	44	76
B757-200	19	55	94
B767-300ER	29	81	140
B747-400	41	117	202
A319	13	36	62
A320	15	42	72
A321	18	51	88
ATR42-300	4	12	20
ATR72-200	6	16	28

All costs are in Euros per minute

[3] Kano et al. (1984) defines a multi-tier approach to customer satisfaction, using "must-be", "one-dimensional" and "attractive" requirements.

III. Marginal crew costs

A. Overview

The calculation of the marginal flight and cabin crew costs derives the cost of crewing for additional minutes over and above those planned at the strategic phase. The costs were derived from a detailed examination of payment mechanisms for aircraft crew, with reference to salary ranges in 2008 and a review of flight and cabin crew payment mechanisms for a wide range of airlines. In Europe, airlines typically pay crew fixed salaries (supplemented by flying time payments) whereas crew in North America are typically remunerated by a 'pay-and-credit' scheme whereby duty and flying time determine the salary (Nissen and Haase, 2006).

From a European perspective (the basis of these estimates), for marginal crew costs incurred by airlines during delay, even delays in excess of an hour could result in no additional costs. For example, an at-gate delay would have no effect on the cost of crew paid *by block-hours worked* as this payment mechanism is triggered off-blocks. An airborne delay will have no effect on the cost of crew paid *by sectors flown* as this payment mechanism is cycles-based. In both cases, a large proportion of pay would normally be fixed as basic salary, with per diem allowances. For this research, proxy rates were calculated for the base case, whilst delay minutes were set at overtime rates for the high cost scenario.

B. Summary of methodology and results

Typical pilot and flight attendant salaries were calculated for various European airlines, using their corresponding payment schemes with realistic annual block/flight duty hours, sectors flown and overnight stopovers. Pilots' salaries increase by size of aircraft, although commonality can be seen within aircraft families (e.g. the A320 family). In contrast, flight attendants' salaries are more consistent across all aircraft types.

In Europe and the US, total cabin crew numbers are driven by the maximum number of seats available. A typical range of seats per aircraft was established using ICAO 2006 fleet data (as per the passenger cost calculation). Unusual aircraft seat configurations were excluded from this range.

These calculations relate to delay costs incurred by the airline, so on-costs need to be included. These cover a range of additional crew-related costs to the airline, such as administration and personnel costs associated with managing crew, company contributions to crew pension schemes and social security/insurance contributions. For a comparison of on-costs for a range of European airlines, see Doganis (2005). The lowest proportion of additional cost was found to be 17-18%, with the highest proportion being an extra 52%. Removing extreme values, the on-cost low to high scenario range was rounded to 20-40%, with the mid-point (30%) adopted for the base cost scenario.

Zero-cost is assigned to the overall, low cost scenario. However, it cannot be assumed that at-gate and airborne hours do not generate additional costs to the airline for the base and high cost scenarios. Although a delay experienced by an individual flight may have no *immediate* effect on the amount paid by the airline to the delayed crew, over a period of time (initially 28 consecutive days, then the calendar year), delays are likely to affect crews' remaining flight and duty hours – limited by Regulation (EC) 1899/2006. Either overtime payments will be paid earlier than would have been the case without such delays (when the hours worked or duty threshold is reached) and/or out-of-hours crew will need to be covered by other/reserve crew. Proxy rates are thus modelled, based on derived 'time-based' salaries for flight and cabin crew, for each aircraft type. The final results are shown in Table 4.

Table 4
Marginal crew costs per aircraft, at-gate or airborne

Aircraft	Low	Base	High
B737-300	0	8.1	16.9
B737-400	0	7.8	17.0
B737-500	0	7.6	16.5
B737-800	0	8.6	18.6
B757-200	0	8.6	17.2
B767-300ER	0	12.2	33.0
B747-400	0	15.9	43.0
A319	0	7.0	14.5
A320	0	7.4	15.4
A321	0	7.4	15.4
ATR42-300	0	5.4	11.0
ATR72-200	0	5.8	12.4

All costs are in Euros per marginal minute. On-costs are included.

The base scenario costs, being proxy rates, are not the rates at which crew would actually be paid, but instead allow the determination of an equivalent marginal (block-) hour crew cost to the airline, based on realistic operational assumptions. They are averaged back over the whole year, allowing typical delay costs to be proportionately spread over crew paid at basic and overtime rates. For the high cost scenario, it is assumed that delay minutes are paid simply at overtime rates.

IV. Marginal maintenance costs

A. Overview

The marginal maintenance costs incurred by delayed aircraft relate to factors such as the mechanical attrition of aircraft waiting at gates, subjected to arrival management, or accepting longer re-routes in order to obtain a better departure slot. The basic principle is to derive marginal, time-based costs from unit costs, by removing fixed costs and correctly apportioning cycles-based costs across marginal delay minutes. Large proportions of maintenance costs are fixed, in terms of overheads, or on a per-cycle basis.

The former is dealt with by separately identifying aircraft-specific overheads (ESG Aviation Services, 2007) and removing them from the cost model. The latter is dealt with by the development of a gate-to-gate 'workload model'.

It was first necessary to develop a pre-cursor model for computing unit maintenance costs. 2006 block-hour (unit) costs were derived from earlier (in-house) 2002 data, using ICAO (2006) Airline Monitor (ESG Aviation Services, 2007) data. These unit costs were then updated from 2006 to 2008 values (using maintenance-specific inflationary factors) before finally translating these unit costs into the appropriate marginal at-gate and cruise costs for 2008 through the gate-to-gate model.

B. *Summary of methodology and results*

For modern aircraft types, 'letter check' distinctions are less important, since maintenance tasks are grouped into packages in a way that is more efficient for the operator, i.e. matching work against operational requirement. Nevertheless, the industry generally still refers to maintenance checks such as 'A', 'C' etc. Table 5 shows typical maintenance check intervals for 'A' and 'C' checks, whereby the newer 'phase' intervals have been converted to letter check intervals.

TABLE 5
TYPICAL MAINTENANCE CHECK INTERVALS

Aircraft	'A' Check	'C' Check
B737-300	275 FH	18 months
B737-400	275 FH	18 months
B737-500	275 FH	18 months
B737-800	500 FH	4000-6000 FH
B757-200	500-600 FH	18 months / 6000 FH / 3000 FC
B767-300ER	600 FH	18 months / 6000 FH
B747-400	600 FH	18 months / 7500 FH
A319	600 FH	18-20 months / 6000 FH / 3000 FC
A320	600 FH	18-20 months / 6000 FH / 3000 FC
A321	600 FH	18-20 months / 6000 FH / 3000 FC
ATR42-300	300-500 FH	3000-4000 FH
ATR72-200	300-500 FH	3000-4000 FH

Key: FC, flight cycles; FH, flight (not block) hours.

Modelling the 2006 unit costs (the most recent full year of airline financial returns, at the time of calculation) from 2002 data was non-trivial. During this period, the cost of maintenance changed in highly variable ways across airlines. Some rose sharply, whilst others had periods of very large falls. Not all of these changes can be explained by changes in the age or composition of aircraft fleets, airline takeovers or maintenance centralisation within airline groups. Due to the lack of clear overall trends, best-fit solutions were obtained by solving a series of simultaneous equations to estimate average narrowbody and widebody maintenance costs per block-hour, with some outlier smoothing (but still taking account of likely upper and lower bounds for the high and low cost scenarios).

These unit, block-hour costs for 2008 (encompassing all maintenance costs, but with overheads subtracted) were then processed through the workload model into marginal at-gate and cruise costs. Per-cycle costs incurred during the highest intensity phases of flight (i.e. from take-off roll to top of climb, and from top of descent to landing roll) were frozen out of the calculations. In these specific phases, although a high share of the total wear and tear is experienced, no delays were assumed. Separate airborne phases were allocated for cruise and arrival management, although these produced very similar results (as expected). Fuel burn rates were used as a proxy for workload to apportion the powerplant costs across the phases.

TABLE 6
MAINTENANCE COSTS BY AIRCRAFT TYPE (BASE SCENARIOS)

Aircraft	Unit cost (per block-hour)	At-gate marginal cost (per marginal minute)	Cruise marginal cost (per marginal minute)
B737-300	740	0.5	3.8
B737-400	760	0.5	3.9
B737-500	620	0.4	3.2
B737-800	540	0.4	2.8
B757-200	900	0.6	4.6
B767-300ER	970	0.6	4.6
B747-400	1 500	1.0	7.1
A319	630	0.4	3.3
A320	620	0.4	3.2
A321	720	0.5	3.7
ATR42-300	370	0.2	1.9
ATR72-200	460	0.3	2.4

All costs are in Euros. Marginal costs exclude overheads.

Notably, the resulting marginal cruise minute costs (Table 6) are similar to literature-sourced values for combined 'A' plus 'C' checks converted to block-minute costs. The implication for airlines is that using 'A' plus 'C' check estimates for marginal minute costings probably gives reasonable estimates of the true marginal cost of maintenance.

The ideal development of this methodology would be to extend it to tail-specific cost tracking. Power-by-the-hour or cost-per-flying-hour maintenance agreements now account for many airline maintenance contracts. Careful analysis of the contract terms, with corrections for fixed (e.g. overhead) costs, is necessary to convert these costs into true marginal minute costs.

V. NETWORK EFFECTS – AN OVERVIEW

The costs discussed in the previous sections need to be scaled up to the network level, since original delays caused by one aircraft ('primary' delays) cause 'knock-on' effects in the rest of the network (known as 'secondary' or 'reactionary' delays). These need to be factored in to any comprehensive assessment of delay costs. An overview of this is given in this section, with the discussion developed further in Section VIII.

Reactionary delays are generally worse for longer primary delays and for primary delays that occur earlier in the operational day (when the knock-on effects in the network are greater). They also depend on the airlines' ability to recover from the delay, for example due to the extent of schedule padding (buffering). Primary delays not only affect the initially delayed ('causal') airframe on subsequent legs (rotational reactionary effect), but also other aircraft (non-rotational reactionary effect).

The 2008 European reactionary to primary delay ratio of approximately 0.8 (EUROCONTROL (2009), see also Section VIII) means that for each minute of primary delay, on average, another 0.8 minutes of reactionary delay are generated in the network. This is often expressed in the literature as a multiplier, 1.8.

Rather than multiplying all delay costs by a common factor (e.g. 1.8) in order to get a value corresponding to the total network cost (primary plus reactionary cost), Beatty et al. (1998) studied delay propagation using American Airlines' schedule data, building delay trees with schedule buffers included in the delay-tree scenarios. Based in part on this model, the multipliers we have developed quantitatively differentiate between rotational and non-rotational reactionary delays and also take into account the magnitude of the primary delay, thus producing multipliers for each delay range in Table 7 (selected mid-range values only shown). In our models, all reactionary delay is treated as at-gate delay, and non-rotational reactionary delay is based on European 'average' aircraft, as described in Section VII.

The use of these reactionary multipliers is not restricted to passenger delay costs, but also applies to marginal delay costs such as those associated with crew and maintenance. Separate methods are used for applying the different types of reactionary multipliers to passenger, long-haul crew, short-haul crew and marginal maintenance costs.

TABLE 7
REACTIONARY MULTIPLIERS AVERAGED OVER DELAY RANGES

Range (mins):	1 -15	16 -30	31 -45	46 -60	61 -75	76 -90	..	300 +
Basic	1.48	1.74	2.00	2.25	2.51	2.77	..	6.47
Rotat.[a]	0.36	0.56	0.75	0.94	1.13	1.32	..	4.11
Non-r.[a]	0.12	0.19	0.25	0.31	0.38	0.44	..	1.37

[a] Rotat. = Additional rotational; Non-r. =Additional non-rotational.

VI. PRE-DEPARTURE AND AIRBORNE DELAY MANAGEMENT

In this section we show how the costs calculated in the previous sections can be combined with fuel and (future) emissions charges to make cost-benefit trade-offs both in the pre-departure and airborne phases of delay cost management.

Fuel burn cost calculations were undertaken (in 2008) using the flight planning application Lido OC (Lufthansa Systems Aeronautics), based on operational flight plans. In addition to these direct fuel costs, the future costs of emissions charges were considered. CO_2 from aviation is scheduled for inclusion in the EU emissions trading scheme from 01 January 2012. In its current form, the legislation requires all airlines operating to or from EU airports to surrender permits for the CO_2 emitted. For the airlines, this will result in all fuel use being associated with an additional carbon permit cost. The European Commission has also committed to developing a flanking policy to address NO_x emissions from aviation by November 2009.

Emissions are estimated using the product of the fuel consumed and the emission index (emission per unit mass of fuel). For CO_2, the emission index is a function only of the fuel and can be considered constant across an aircraft fleet. Fuel consumption above 3000 ft was used for the NO_x calculations; below this level NO_x emissions are important for air quality considerations but not for climate impact. Estimates of NO_x emissions took into account aircraft type and route length. For illustration only[4], costs were sourced from ENVISA (2006), which assigns the climate impacts of CO_2 emissions at € 37 / tonne and those of NO_x at € 6414 / tonne, for a base case scenario.

Fig. 3 shows how these calculations may be used to compare at-gate costs with cruise extension costs for a given delay duration, aircraft and cost scenario5. In this case, the at-gate (auxiliary power unit and engines off) cost is € 1109, whilst the cruise extension cost is € 1948. The latter is higher primarily due to fuel burn and emissions charges.

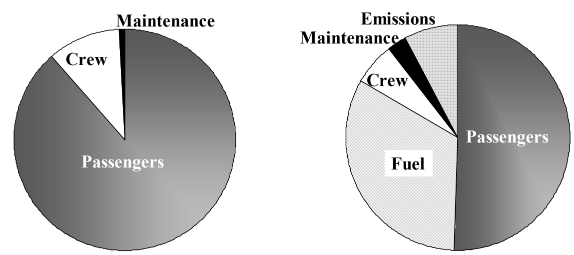

Fig. 3. B738 at-gate (left) and cruise extension (right) costs (20 minutes)

The key application of comparisons such as these is for pre-departure operations, e.g. trading the costs of bringing a delayed take-off slot x minutes forward against a re-route that is y minutes longer6, and for informing the process of airspace design.

In decision-support for *airborne* delay recovery, it is necessary to trade accelerated fuel burn costs (and, from 2012, emissions charges) against these costs of delay.

[4] Emissions costs can only be an estimate at this time, as the price will depend on the design and implementation of emissions policy.

[5] Base cost scenarios are shown, including the reactionary delay effects outlined in Section V; cost of fuel (2008): € 0.7 / kg.

[6] In Fig. 3, x = y = 20 minutes, as a simple comparison. See Cook et al. (2004) for proper worked examples.

Since many airlines have significant barriers to quantifying such delay costs, they may use simple 'rules of thumb' to set the value of the cost index (see Table 1B). Of the (non-fuel/emissions) components of delay cost (i.e. passenger delay, crew and maintenance costs), it is clear from Fig. 3 that the passenger cost dominates (this is very often the case, except for the smallest delays).

Fig. 4 shows a quantitative example of such a cost trade-off for a B738, which has incurred 22 minutes of delay on a flight from Lisbon to Helsinki. The dashed vertical line (right) represents the maximum number of minutes (19) that may be recovered by employing the cost index at its upper operational setting. The net benefit plotted is the difference between [(cost of delay) – (cost of fuel + emissions)], before and after the delay recovery applied (x-axis). Each curve represents different cost assumptions (from top to bottom: without emissions charges, fuel at € 0.5 / kg; without emissions charges, fuel at € 0.7 / kg; with emissions charges, fuel at € 0.7 / kg). The optimised number of recovered minutes is 12, 11 and 10 for the respective cost assumptions. The plot illustrates, for example, that when fuel is cheaper, it is optimal to recover more time and that recovering the full 19 minutes when fuel is more expensive and emissions charges apply, actually generates a net loss. For the latter assumption, recovering 19 minutes instead of the optimal 10 minutes, for twenty such B738 flights a day, would cause an estimated, relative annual loss of approximately € 6.7 million.

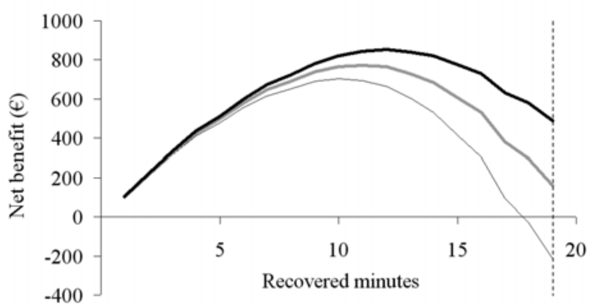

Fig. 4. Net benefit of airborne recovered minutes for a B738

VII. FLOW MANAGEMENT – COSTS AND TARGETS

In this section we make a fairly crude estimation of the primary cost of the 2008 distribution of ATFM (delay) slots, drawing on the results of sections II-IV. By 'delay' slot, we are referring to ATFM slots issued for aircraft departures later than the time requested by the airline. We compare these costs with hypothetical scenarios under different distributions of ATFM delay, as an initial exploration of the implications for ATFM target-setting.

Fig. 5 shows the distribution of ATFM delay minutes in 2008 (data courtesy of Performance Review Unit, EUROCONTROL). The data refer to Instrument Flight Rules flights and, for ease of exposition, only those flights with ATFM delay are plotted, although 88% had no ATFM delay: these 'zero-delay' flights are, however, included in all the analyses which follow. Of course, many of these flights will have incurred *compound* delays, whereby only part of the total flight delay is due to ATFM (as discussed in Section VIII).

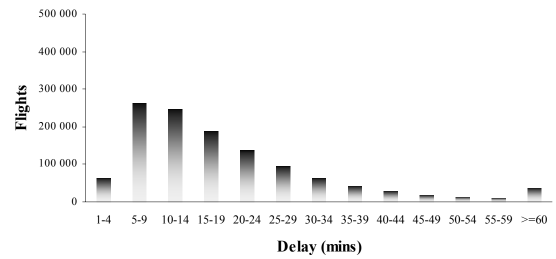

Fig. 5. ATFM delay distribution (2008, actual).

Including the 'zero-delay' flights, the 2008 ('actual') distribution has a mean delay of μ=2.4 minutes, and, making a simplifying assumption for the mid-point of the highest-delay column, a standard deviation of σ=8.5. (Excluding the zero-delay flights, the average of delay slots issued is around 20 minutes.)

It is possible to estimate the total primary cost of delay by taking the mid-point of each range and multiplying this by the cost per minute for passenger hard and soft costs, plus the crew and maintenance costs derived above, using a 2008 'average' aircraft. This 'average' approximation was carried out by weighting the costs for the 12 supported aircraft by their relative flight frequencies in 2008 (data, not shown, courtesy of EUROCONTROL Statistics and Forecast Services – STATFOR). Since these costs of delay are dominated by passenger costs, the average aircraft used could, if desired, be quite closely approximated by either an A320 or a B738, which were also the two most common aircraft in Europe in 2008 in terms of number of flights or total flight-hour duration. Load factors were as per Section II(c).

The total cost estimate using this method is €1.7bn. Although the validity of the comparison is significantly limited, it is of some passing noteworthiness that EUROCONTROL (2009) estimates the total cost of ATFM delays in 2008 to be €1.5bn. This is quoted in 2007-Euro prices, currently uses a common value of €79 per minute for delays of above 15 minutes, and approximates costs to be close to zero for the first 15 minutes.

Both these estimates (€1.7bn; €1.5bn) are derived from a number of common principles, and refer to at-gate delay without engines running. However, whilst the €1.7bn estimate is in 2008-Euro prices and estimates separate costs for each delay range, it notably excludes reactionary costs, unlike the EUROCONTROL value. Instead of dwelling on the comparison of these estimates, we turn our attention to the relative costs under different scenarios, using the mid-range method described.

Fig. 6 shows the trivial distribution, scenario 1, obtained by removing half of the flights in each delay category and moving them into the zero-delay category (not plotted). The figure is shown primarily for the purposes of inclusiveness.

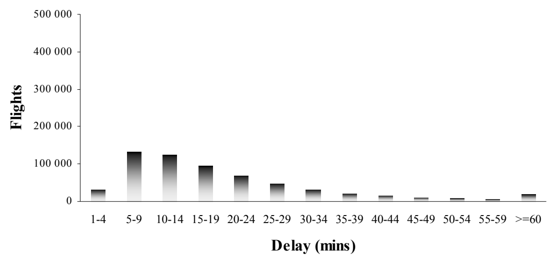

Fig. 6. Scenario 1 – delay frequencies halved.

For each scenario the data are summarised in Table 8; the total number of flights and the proportion of (remaining) plotted columns is always the same as for the 2008 (actual) distribution. The halving under scenario 1 simply halves both the mean delay (50% of 2008 value) and the total (primary) cost of delay. Although 94% of flights now have no ATFM delay, the standard deviation is still 72% of its original value.

In scenario 2 (see Fig. 7) the columns are removed from the 2008 actual values, in turn, working from right to left, redistributing each column of flights according to the original proportions to their left (including the zero-delay category), until the total cost has been (practically) halved (51% of original, see Table 8). Scenario 2 has a very similar standard deviation to scenario 1, although this time the mean has remained at 74% of its original (2008) value. From the airline perspective, a key advantage of scenario 2 is that although it has both a similar cost and standard deviation to scenario 1, there are no ATFM delays in the '≥60 minutes' category (indeed, there are none greater than 39 minutes). Of these two theoretical scenarios, scenario 2 would thus be the one we may expect to be preferred by the airlines.

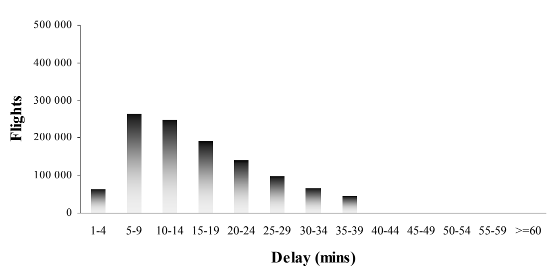

Fig. 7. Scenario 2 – redistributed from right until cost halves.

From an ATFM perspective, however, the absence of all the highest slot delays would be impractical. Scenario 3 (Fig. 8) removes four fifths of the original, highest ATFM slot delays (i.e. in the '>=60 minutes' category) and also all of the 20-59 and 1-4 minutes delay categories, redistributing these (according to the original proportions) across the (three) 5-19 categories. This reduces the overall cost to a third of the original value (see Table 8), also retaining the original number of zero-delay flights (88%).

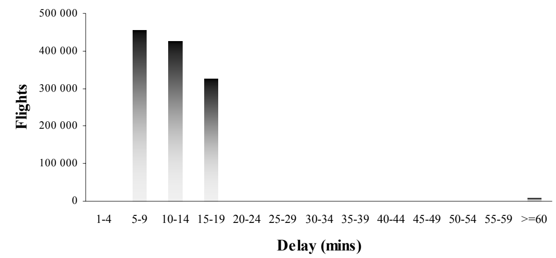

Fig. 8. Scenario 3 – rendered bimodal, with small tail.

Scenario 3 increases the number of flights with slot delays of less than 20 minutes by a factor of around 1.6, compared with the original distribution, and almost *halves* the original standard deviation (much of which is contributed by the right-hand tail).

TABLE 8
COMPARISON OF ATFM SCENARIOS WITH 2008 (ACTUAL)

Scenario	% relative to 2008			% delays (mins)		
	Cost	**μ**	**σ**	**0**	**<20**	**≥60**
Actual	100	100	100	88	7.5	0.36
1	50	50	72	94	3.7	0.18
2	51	74	68	89	7.6	0.00
3	33	60	53	88	12	0.07

Values quoted to 2 s.f.

The main purpose of this discussion is to explore the cost implications for different types of ATFM delay distributions, rather than the extent to which such distributions may be realised through new slot-allocation algorithms. Scenario 3 is likely to be somewhat more achievable than scenario 2 and illustrates the point that a shift towards a more bimodal distribution may achieve a significantly lower airline cost even with a higher mean (c.f. scenario 1) and with increased predictability. This latter improvement in predictability (reduction in standard deviation) may bring further financial benefits by prompting airlines to reduce their schedule buffers (with associated strategic cost savings – see Table 1A). In the specific case of scenario 3, this is reflected by the strong domination of delay slots in the 5-19 minutes range, although less pronounced shifts in such patterns may have significant scheduling effects for airlines, especially those statistically modelling their schedules based on empirical delay.

The European target (adopted by the Provisional Council of EUROCONTROL in 2007) for en-route ATFM delay is one minute per flight, until 2010 (EUROCONTROL, 2009). This target refers to en-route ATFM delay in the summer period (May to October) and includes all causes (capacity, weather, etc.). In 2008, summer en-route ATFM delays increased for the fourth consecutive year, to 1.9 minutes per flight. This was the highest value since 2001, despite the notable slowdown in traffic growth. This specific target corresponds approximately to a halving of the current mean. The preceding discussion has explored, in outline, different ways in which delay reductions may be expressed, with two scenarios (2 and 3) where the cost halved (or better), but the mean did not.

It is clear, however, that there are constraints on setting separate targets for mean delays, associated standard deviations, and the resulting net cost. These three will obviously tend to move in the same direction at the same time. Although we have intentionally set out to explore scenarios in which this is not the case, the actual trend over the period 2003-2008 has been for a linear relationship between μ and σ (r^2=0.93; raw data, not shown, courtesy of Performance Review Unit, EUROCONTROL). This relationship is, of course, based on the same fundamental principles applying to slot allocation over this period, and need not pertain in the future.

These illustrative analyses are subject to a number of approximations and limitations. The main issues are that: (a) the tail of the distribution is not analysed in detail – instead, all delays above 60 minutes are assigned a common value; (b) reactionary delays are not included; (c) the ATFM delays are treated as pure delays, without taking into account that they often occur as a compound delay along with other causes; (d) an average aircraft is used, rather than matching each delay with the actual aircraft affected.

As for (a), the treatment of the tail remains a problem, unless every explicit delay has a delay cost quantified for it. The more, higher delay values, which are explicitly quantified, the better the approximation, but the results will remain approximations only. Notwithstanding the limitations of the approximations in this paper, the general principles revealed remain valid. Furthermore, at higher delay values, the issue of cancellation costs need to be considered. The limitations of (b) and (c) are related, and will be discussed in Section VIII. Of these factors, (a) – (d), (d) is anticipated to have the least quantitative impact on the results outlined here.

The extent to which any future change in ATFM delay distributions is desirable, also depends on other factors. One such is airline preference. The preferred distributions for airlines could be deduced from stated preference studies similar in approach to that of Bates et al. (2001), presenting rail passengers with similar trade-offs between the means and standard deviations of delay, as a function of associated cost. These authors identify a particular pitfall which needs to be avoided, in that: "there is a suspicion that respondents are protesting about the unreliability of public transport services, and therefore manifesting excessive disutility from late arrival". Such trade-off exercises with airlines should best be performed with realistic cost data for the airline, in order that meaningful choices may be made. These would ideally even be integrated with an appropriate statistical scheduling model. It is also clear that ANSP costs should be considered in the provision of any future, adapted approach to flow management. A solution which offers reduced costs to the airlines is of no net benefit if the cost of providing the solution, as passed on in en-route charges, for example, more than off-sets such savings.

VIII. Conclusions and future work

Although the major component of airline delay cost is typically that associated with delayed passengers, this is generally poorly quantified. A major opportunity, and challenge, facing the airline industry is the integration of disruption management techniques into flight planning. Costs such as those estimated in this paper could be used to inform improved decision-making in delay recovery, superior to 'rules of thumb' currently employed by many airlines. A superior solution would be the calculation of such costs *dynamically*, through the enhancement of existing passenger reaccommodation tools to interface with airborne delay recovery – this could furnish airlines with large savings.

Best economic practice is unlikely to be consistent with arbitrarily set punctuality targets, such as "99% of flights within 5 minutes of schedule". If used at all at this generic level, such targets need to be set within the context of cost-benefit analyses. For example, what is the alternative bottom-line impact of instead targeting 98% of flights within 10 minutes of schedule? Again, use of 'rules of thumb' (such as recovering all the delay when it exceeds 15 minutes) can cause severely negative financial impacts.

Disruption management processes, including passenger reaccommodation, directly affect aircraft turnaround times. These are a key component of overall air traffic management (ATM) efficiency: "Air transport delays originate principally from local turn-around delays (76%), i.e. ground processes under local control outside the remit of ATM. This is an area for improvement and there should be consistency in the accuracy of ground and air-side processes in advanced concepts such as SESAR[7]" (EUROCONTROL, 2008).

There is also a particular need for further research into reactionary effects, especially the distribution of these between rotational (most of the reactionary delay) and non-rotational components, and across individual, subsequent legs. This is necessary in order to better compute the large effect these have on total costs, since an assumed 60-minute reactionary delay is greatly more expensive than 6 delays of ten minutes.

The general superiority of passenger-centric metrics is of significance for delay measurement, although *flight* delays are still the only commonly-reported type of metric in both the US and Europe. The former also better capture the true impact of diverted and oversold flights. Better reactionary models, e.g. tracking tail-specific data throughout the operational day, would ideally examine passenger (and crew) dependencies between delay-impacted aircraft and improve the understanding of the relationships between passenger-centric metrics and reactionary effects.

Data from the EUROCONTROL Central Office for Delay Analysis (CODA) show that the reactionary to primary delay ratio has worsened year-on-year from 2003 to 2008, EUROCONTROL (2009). Despite a slowing down of European traffic growth in 2008 to 0.4% (compared with 5% in 2007; EUROCONTROL (2009)), the reactionary to

[7] The Single European Sky ATM Research programme, the European analogue of NextGen in the US.

primary delay ratio still increased a little: from 0.81 in 2007, to 0.83 in 2008. Tighter airline schedules and turnaround times, as well as higher levels of aircraft and airport utilisation, all contribute to an increased ratio. This can be in response to traffic growth and/or increased economic pressures on efficiency. With traffic 'growth' expected to be negative in 2009 (-3%), the ratio can be expected to fall, although there is probably a lag effect with operational practice.

Increased unpredictability (higher standard deviations) further compounds the problem of reactionary delay, unless airlines are able to appropriately adjust schedule buffers. This is clearly linked with the discussion of Section VII. ATFM-related departure delays showed an increasing trend in 2008, and accounted for 27%[8] of such delays, for en-route and airport constraints combined (EUROCONTROL, 2008). Cost estimations such as those of Section VII need to respect this wider context, taking at least some account of the dependencies between ATFM and non-ATFM delay. For example, if an aircraft misses its original slot due to a slow turnaround, and the subsequently re-filed flight plan has a high ATFM delay, it may be argued that no component of the final delay should be attributed to ATFM. On the other hand, ATFM delays may often be less easy to anticipate for the airline than certain other types of delay, and may occur closer to the planned departure time, such that the *reactionary* consequences may be relatively worse. These may be ambitious objectives to address quantitatively, but there is doubtless scope for further research.

This paper has explored a number of aspects of the distribution of delay costs across cost components, magnitudes of delay, phases of flight and reactionary modes. It has also examined the cost implications for different distributions of ATFM delay. An understanding of these distributions offers valuable insight into significant associated economic and environmental impacts. Neither delay management processes, nor flow management targets, should be restricted in scope to a consideration of delay minutes alone.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the generous support of the European Organisation for the Safety of Air Navigation (EUROCONTROL) for enabling this research to be carried out. This work 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.

The authors further acknowledge work previously undertaken with Lufthansa Systems Aeronautics and Imperial College London, also funded by EUROCONTROL, which respectively produced the fuel burn and emissions computations used in Section VI.

[8] 24% without weather-related ATFM delays.

REFERENCES

Bates, J., Polak, J., Jones, P., Cook, A. (2001). The valuation of reliability for personal travel, Transportation Research Part E (37), 191–229.

Beatty, R., Hsu, R., Berry, L. and Rome, J. (1998). Preliminary evaluation of flight delay propagation through an airline schedule, 2nd USA/Europe Air Traffic Management R&D Seminar, Orlando.

Bratu, S. and Barnhart, C. (2004). An analysis of passenger delays using flight operations and passenger booking data, Sloan Industry Studies Working Paper WP-2004-20. Available: http://www.industry.sloan.org.

Bratu, S. and Barnhart, C. (2006). Flight operations recovery: New approaches considering passenger recovery, Journal of Scheduling (9), 279–298.

Cook, A., Tanner, G. and Anderson, S. (2004). Evaluating the true cost to airlines of one minute of airborne or ground delay, University of Westminster, for EUROCONTROL Performance Review Commission, Brussels.

Cook, A., Tanner, G., Jovanović, R. and Lawes, A. (2009).The cost of delay to air transport in Europe – quantification and management,13th Air Transport Research Society (ATRS) World Conference, Abu Dhabi, June, 2009.

Cook, A., Tanner, G. and Lawes, A. (2009a). The hidden cost of airline unpunctuality. Working paper for EUROCONTROL Experimental Centre; journal paper in preparation.

Cramer, K. and Irrgang, M. (2007). Disruption Costing Methodology: ValSim – visualization and simulation of airline operations (Boeing Commercial Airplanes), AGIFORS (Airline Group of the International Federation of Operational Research Societies) Airline Operations Conference, Denver.

Doganis, R. (2005). The Airline Business (2nd Edition), ISBN 0415346142, Routledge.

ENVISA (2006). Project GAES - Environmental Impact of Delay, SEE Note No. EEC/SEE/2006/006, prepared for EUROCONTROL Experimental Centre by ENVISA, Paris.

ESG Aviation Services (2007). Block hour operating costs by airplane type from 1968 or the first year of delivery, 'The Airline Monitor'.

EUROCONTROL (2008). Performance Review Report 2007: An Assessment of Air Traffic Management in Europe during the Calendar Year 2007, EUROCONTROL Performance Review Commission, Brussels.

EUROCONTROL (2009). Performance Review Report 2008: An Assessment of Air Traffic Management in Europe during the Calendar Year 2008, EUROCONTROL Performance Review Commission, Brussels.

ICAO (2006). Digest of Statistics. Available: http://www.icaodata.com.

Jovanović, R. (2008). The cost of passenger delays to airlines: an assessment of the impact of the regulation (EC) 261/2004, 12th Air Transport Research Society World Conference, Athens.

Kano, N., Seraku, N., Takahashi, F. and Tsuji, S. (1984). Attractive quality and must-be quality, Hinshitsu (14, 2), 39–48.

Kohl, N., Larsen, A., Larsen, J., Ross, A. and Tiourine, S. (2007). Airline disruption management — Perspectives, experiences and outlook, Journal of Air Transport Management (13), 149–162.

Narasimhan, R. (2001). Is there ultimately only one application needed for improving airline reliability? (United Airlines), AGIFORS (Airline Group of the International Federation of Operational Research Societies) Airline Operations Conference, Ocho Rios.

Nissen, R. and Haase, K. (2006). Duty-period-based network model for crew rescheduling in European airlines, Journal of Scheduling (9), 255-278.

Sherry, L., Wang, D., Xu, N. and Larson, M. (2008). Statistical comparison of passenger trip delay and flight delay metrics, Transportation Research Board 87th Annual Meeting, Washington DC.