UNIVERSITY OF WESTMINSTER

European airline delay cost reference values

Final Report (Version 3.2)

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3.2	3.2	31 MAR 11	Submitted to PRC	Final revision

Note

 This work is part of longer-term research. At this stage, the results represent the view of the University of Westminster and do not necessarily reflect the official view of EUROCONTROL's Performance Review Commission. Financial and traffic data available at the time of production of Version 0.4 have been used in all subsequent versions. Annex J was added to Version 3.1. Annex K was added to Version 3.2.

Executive Summary

Context

This report is an update and extension of work published in 2004, also produced by the University of Westminster. This new report takes into account, as far as possible, relevant changes in the economic and regulatory environment since the earlier work. Whilst account has also been taken of the limited literature since 2004, the authors are not aware of any other new work comprehensively addressing European airline delay costs. Cost comparisons between the values reported earlier and the 2010 values are in unadjusted Euros, unless stated otherwise.

The report is designed as a reference document for European delay costs incurred by airlines, both at the strategic (planning) and tactical stages. Quantifying these costs is essential to the objectives of SESAR, offering future solutions to the airspace user, which are focused on the "best business outcome"*. It includes extensive tabulations of costs and guidelines on how to use them.

The results may be used by airline operators to gain operationally meaningful insights into typical European delay costs, a pre-requisite of delay cost management, including trade-offs between delays in different phases of flight (e.g. en-route and at-gate) and for a range of specific aircraft types and cost scenarios, reflecting different airline cost bases.

The results may equally be used by policy makers and airspace managers and designers to quantify the benefits of improved service delivery (such as more direct routes, fewer aircraft delays at-gate, etc.).

Assigning these costs is complex and draws on a wide range of disciplines, with relatively little published elsewhere with regards to quantifying European costs. A number of the costs modelled necessarily draw on expert judgement and assumptions, based on published statistics and robust data wherever possible. This report has been circulated to airlines and other stakeholders for feedback and many key aspects have been presented at major air transport conferences. Nevertheless, as with any such research, some caution is indicated in the use of the findings: such limitations and the need for further work are identified in the text.

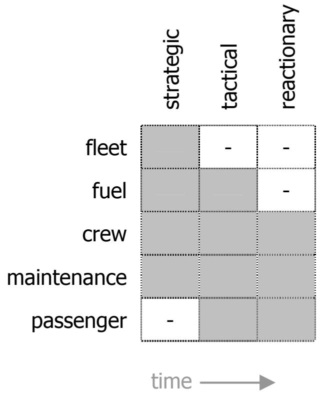
Strategic, tactical and reactionary costs

The cost of delay is calculated separately for strategic delays (those accounted for in advance) and tactical delays (those incurred on the day of operations and not accounted for in advance). The type of strategic cost focused on is adding buffer to the airline schedule.

It is assumed that the amount of buffer to be used throughout the schedule is yet to be decided, whereas the number of cycles (rotations) on a particular airport-pair for a given day and season has already been decided.

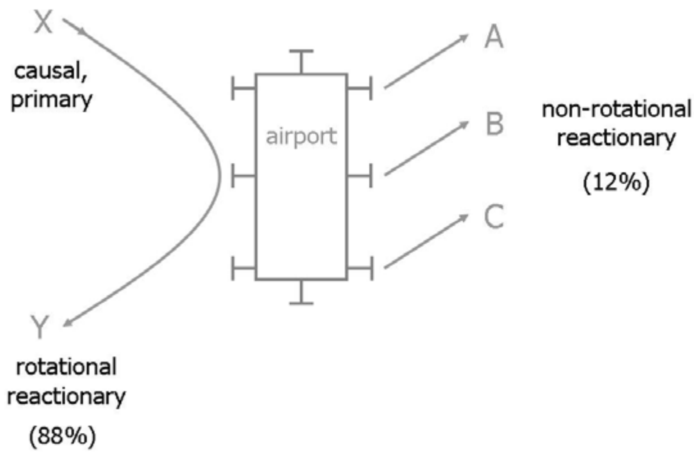
Tactical delay costs are given for 5, 15, 30, 60, 90, 120, 180, 240 and 300 minutes. These are scaled up to the network level because on the day of operations, original delays caused by one aircraft ('primary' delays) cause 'knock-on' effects in the rest of the network (known as 'secondary' or 'reactionary' delays).

* Strategic Guidance in Support of the Execution of the European ATM Master Plan. EUROCONTROL Stakeholder Consultation Group (Edition 1.0, May 2009).



The figure shows which cost types are assessed at each level. Strategic costs and tactical costs are not independent: reactionary delays 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 tactical costs would be significantly higher.

Primary delays not only affect the initially delayed ('causal') aircraft (flight 'X') on subsequent legs (rotational reactionary effect, e.g. flight 'Y'), but also other aircraft (non-rotational reactionary effect, flights 'A', 'B', … etc).



In 2009, in Europe, for each minute of primary delay, on average, another 0.8 minutes of reactionary delay were generated in the network. For both 2008 and 2009, the ratio of rotational to non-rotational delay minutes was 88:12. These values refer to the system level and can vary significantly by airline.

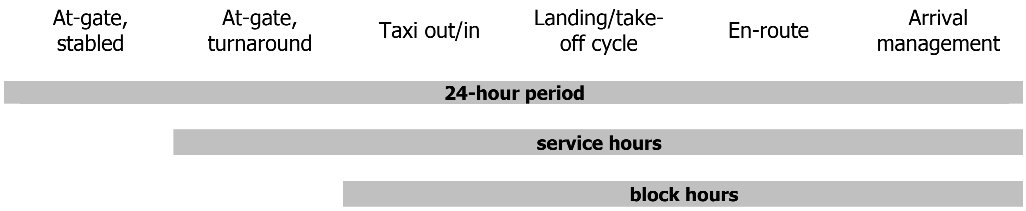
The calculations take into account the magnitude of the primary delay (larger primary delays tend to cause more reactionary delay). All reactionary delay is treated as at-gate delay, differentiated by rotational and non-rotational delay. Caps are applied to rotational delays at costs comparable with the cost of cancelling a flight.

Reactionary delays in the model are usually split over a number of rotations, as it is less likely that all the reactionary delay would occur in a single lot. Different models are used for narrowbodies and widebodies, and for different types of cost (fuel, passenger, crew and maintenance).

At lower delay, recoveries between rotations are accounted for. These are largely made through schedule buffer and slack-time at-gate, and sometimes by achieving a faster turnaround at the gate.

Flight phases

This report presents costs of delay by four flight phases: at-gate, taxi, cruise extension and arrival management (tactical only). Block hours are defined as the time spent off-blocks (aircraft utilisation). Service hours are defined as the total time spent in service during the operational day.



Cost assignments

Costs are assigned under three cost scenarios: 'low', 'base' and 'high'. These scenarios are designed to cover the likely range of costs for European operators. The 'base' cost scenario is, to the greatest extent possible, designed to reflect the typical case. All calculations are undertaken for twelve core aircraft: B733, B734, B735, B738, B752, A319, A320, A321, AT43, AT72, B744 and B763.

Cost of fuel

The cost of fuel burned per minute is calculated for the three off-gate phases. Fuel costs are presented in Section 2.2; fuel burn rates are given in Annex F. The same values are used for the strategic and tactical calculations. A fuel carriage penalty is applied to arrival management.

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. The average European cost did not change from 2002 to 2008. A small increase (5%) was then applied to produce 2010 values.

For the tactical values, marginal, time-based costs are derived from unit costs. Overheads are first removed and then a gate-to-gate model is used to apportion the maintenance cost between the airframe/components and powerplants across flight phases.

The high intensity landing/take-off cycle maintenance costs (approximately 50%) are also excluded from the tactical calculations.

Both strategic and tactical at-gate costs are relatively low (compared to the other phases) because relatively little wear and tear on the airframe is experienced at-gate and the engines are off for the vast majority of this time.

Separate airborne maintenance costs for cruise and arrival management are not allocated, since these would produce very similar results. A common 'airborne' value is assigned.

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. 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. The 2010 base scenario values are 20 – 35% lower than the 2002 values.

Crew costs

Typical pilot and flight attendant salaries were calculated in 2008 for various European airlines, using their corresponding payment schemes with realistic annual block/flight duty hours, sectors flown and overnight stopovers. To update the 2008 costs to 2010 values, pay deals since 2008 for ten European airlines are considered.

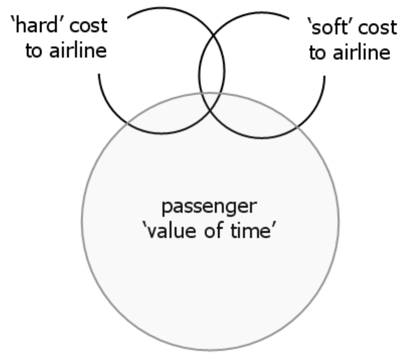
Pilots' salaries generally increase by size of aircraft. Flight attendants' salaries are more consistent across all aircraft types. In Europe, airlines typically pay crew fixed salaries, supplemented by (relatively) small flying-time payments and (cycles-based) allowances. Total cabin crew numbers are driven by the maximum number of seats available (as in the US).

Tactically, cycles-based pay is subtracted from the annual, total cost estimates such that the remaining proportion of the salary is more accurately 'time-based'. Lower amounts of overtime per average service hour are assigned to the strategic phase, compared with the tactical costs, but not to any low cost scenarios. Airline on-costs are included strategically and tactically.

Tactically, in certain cases, delays may not generate additional crew costs, and the low cost scenario is set at zero cost. The high cost scenario is based on overtime rates. The base cost scenario is based on typical time-based costs. The crew costs commonly apply to ground and airborne phases.

Passenger costs - different types

This report 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 this report. See Annex C for further discussion. 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.

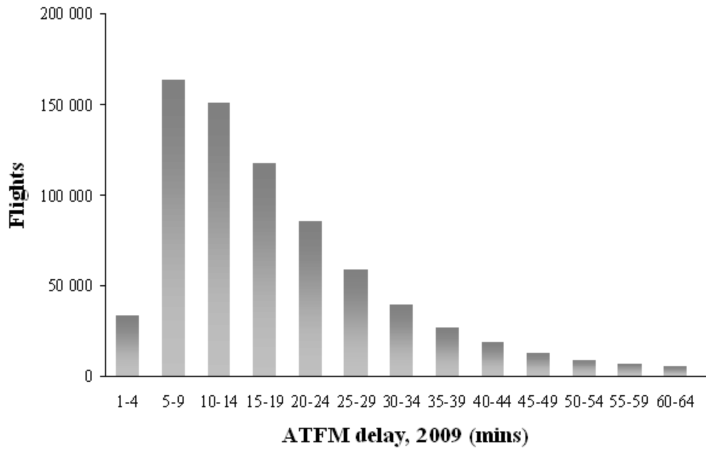
'Soft' costs manifest themselves in several ways. Due to a delay on one occasion, a passenger may defect from an unpunctual airline as a result of dissatisfaction (and maybe later come back). A passenger with a flexible ticket may arrive at an airport and decide to take a competitor's on-time flight 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.

These passenger costs have been previously derived from two European airlines' data for 2003. Since then, 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.

Longer passenger delays will tend to have higher *per-minute* costs than shorter ones. Drawing on typical seat allocations and load factors, these values are translated into per-aircraft costs for each of the twelve supported aircraft.

The passenger soft cost of delay needs to be treated specially when multiplied over a period of time or a network. This is discussed in Section 3.6.20. Other costs are not affected in this way.

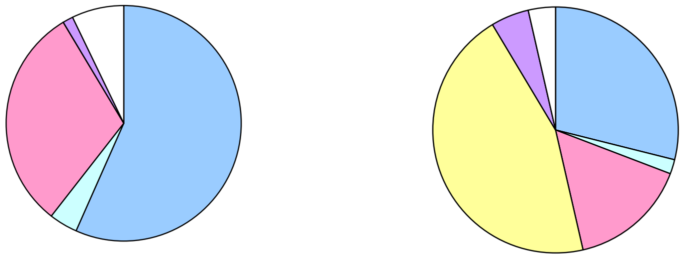
ATFM delay context



92% of flights in 2009 had no ATFM delay. 748 830 flights had some ATFM delay (all causes included, [10]) with the distribution shown in the figure.

Key results

Passenger costs dominate at-gate delays (and hence reactionary costs), whilst fuel costs form a significant proportion of en-route delay costs at lower delay. Example cost distributions for 15 minute delays for a B738 are shown below (see tables 26 and 28 for (other) aircraft totals).



B738 at-gate (EUR 440)   B738 en-route (EUR 860)

Pax hard | Pax soft | Crew | Fuel | Maintenance | Reactionary

Numerous tables have been presented in the report offering detailed cost breakdowns. Where average values are quoted, it is strongly recommended that these are used as indicators and/or insights into delay costs, and not for specific analyses or operational planning. The calculation of a single-flight trade-off, i.e. costs for one tactical decision, is discussed in Annex D.

European ATFM delay cost estimates

Factor	Cost
Network total cost of ATFM delay (all causes)	**1 250 million**
Average cost of delay of an ATFM delayed aircraft	**1 660**
Network average cost of ATFM delay, per minute	**81**

Costs in 2010 Euros. Delay weights use 2009 ATFM data.

The total cost of European ATFM delay (for all causes and including reactionary costs) is estimated as EUR 1 250 million. With 92% of flights incurring no ATFM delay, the average cost of delay of an ATFM delayed flight is EUR 1 660. Dividing the total ATFM delay cost by the total number of ATFM minutes gives an average value of EUR 81 per minute.

Changes compared with previous reporting

Strategic costs are based on unit costs both here and in the 2004 report. Fuller supporting evidence for this approach is presented in Annex K, including a rationale for moderately increasing the high cost scenario values to reflect potential diseconomies of scale when adding buffer to the airline schedule. The at-gate strategic costs have fallen since the earlier report. Some en-route costs are unchanged, whilst others have increased, or decreased, by up to 20%.

Tactically, passenger costs dominate at-gate delays and reactionary costs, whilst fuel costs form a significant proportion of en-route delay costs at lower delay. Overall, the aggregate, total passenger base cost scenario for 2010 is 22% higher than the 2004 value (with the full soft cost included, to compare like with like). 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.

The cost of fuel over this period has doubled: the base cost value in 2004 was 0.31 EUR/kg; in this report it is 0.60 EUR/kg. Maintenance costs have increased only slightly over this period, whereas the (strategic) fleet 2010 base scenario values are 20-35% *lower* than 2002 values.

In addition to changes in the underlying costs, several methodological refinements have been implemented in this report. In the 2004 calculations, tactical crew costs assigned for delays of up to 15 minutes were zero, as were the passenger costs of delay to the airline in the base scenario. Refinements to these models have now allowed costs to be assigned to these shorter delays (which are, in fact, the most common ATFM delay duration, as illustrated in the figure above). In addition, passenger soft costs have been treated in such a way that they may be multiplied over a period of time or a network.

Whereas in the 2004 calculations reactionary multipliers were applied differentiating by two types of delay (i.e. up to, or over, 15 minutes), the new model not only quantifies each reactionary delay as a function of the magnitude of the primary delay, but also more realistically assigns these costs over several rotations and applies caps.

Summary of improvements/changes compared with previous report

Cost (base scenario)	2004 report	This report
Pax hard cost	Treated as zero for <15 minutes of delay	Major update - full cost curves (power curve) derived as function of primary delay
Pax soft cost	Treated as zero for <15 minutes of delay	Major update - full cost curves (logit curve) derived as function of primary delay; scalability now accounted for: small fraction of total now used in most contexts
Crew	Treated as zero for <15 minutes of delay	Extensive new model addressing crew payment schemes and overtime rates; costs assigned to all delay magnitudes
Maintenance	Overheads not fully assessed; costs based on block-hour costs	Overheads fully assessed; cost base extended and re-calibrated on full ICAO data sets
Fleet	Major model developed, based on extensive financial literature	Cost base extended and re-calibrated on full ICAO data sets, supplemented with update from financial literature
Fuel	0.31 EUR/kg	0.60 EUR/kg; carriage penalty now applied to arrival management
Reactionary	Two multipliers: one for below 15 minutes of delay, one for above	Extended model: multipliers fully quantified as function of primary delay magnitude, caps applied using new rotationary models

A crude inflationary increase[†] of the average cost of an ATFM delay minute in 2004 (EUR 72; [1]) to 2010 Euros produces a value of EUR 81 (the same as the newly derived value cited above). The 2004 value was based on delays of over 15 minutes only. The newly derived 2010 value in this report is applied across all delay minutes and is weighted across ATFM delay frequencies. Importantly, costs are now assigned at lower delay values where ATFM delays occur more often. As summarised in the table above, the new methodology has a number of other enhancements, including new passenger cost models and an improved reactionary model.

[†] See 'Euro area' inflation values in Table E1. For the years 2004 and 2010, half the total annual values are used, as a crude method of producing a mid-point 2010 estimate from a mid-point 2004 value.

It is important to note that although the same result is obtained for the average cost of an ATFM delay minute through a simple inflationary increase, such high-level changes may conceal underlying cost factors, which have not changed in line with inflation, as mentioned above. It cannot be assumed that a simple inflationary method would produce similar agreement with high-level values modelled in future. (See also under 'Future work and updates').

It has been demonstrated that √MTOW offers, in theory and empirically, a good linear fit for the full tactical cost of delay. This allows the calculations to be extended to other aircraft, beyond the core set of twelve, to produce European high-level values.

Future work and updates

Estimates of future emissions costs are not included in this report. These could readily be added to future versions of these calculations. CO_2 from aviation is scheduled for inclusion in the EU emissions trading scheme from 01 January 2012. 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.

Section 5 outlines key opportunities for further study. Two dominating costs driving the total tactical cost of delay are passenger costs and reactionary costs, yet these are rarely quantitatively modelled in the literature. Section 5 thus focuses on passenger and reactionary models, but also identifies cancellation costs, broader delay metrics and accelerated fuel burn as future research areas, concluding that all these domains will support newly quantifiable relationships between the performance and cost of future 4D trajectories.

Planned future work will fit simplified, yet robust, total delay cost curves for different phases of flight. It is anticipated that these will employ the √MTOW method of Annex J to extend the model to other aircraft types and will enable users to estimate delay costs based on a number of simple, available, input parameters. It would also be desirable if these new models included a simplified way of updating the costs in future (at least to a reasonable approximation) based on the methodologies of this report and with some degree of user-defined input.

Contents

List of main tables

See also tables in annexes, numbered according to annex letters,
e.g. Table B1 is first table in Annex B.

1 Introduction

1.1 Overview of Report

1.1.1 This report summarises the calculation of the cost of delay to European airlines for four flight phases: at-gate, taxi, cruise extension and arrival management. It is an update and extension of work published in 2004 [1]. This new report takes into account, as far as possible, relevant changes in the economic and regulatory environment since 2004. The cost tabulations are in 2010 Euro-values. Cost comparisons between the values reported earlier and the 2010 values are in unadjusted Euros, unless stated otherwise.

1.1.2 The report is written for the professional reader and assumes an understanding of air transport and ATM. It is designed as a reference document for European delay costs incurred by airlines. It includes extensive tabulations of costs and guidelines on how to use them. Departure delay is assumed to equal arrival delay (see also Annex D).

1.1.3 Reference will be made more specifically to the flight phases and basic definitions in Figure 1. 'At-gate, stabled' refers to time spent at-gate when the aircraft is inactive (e.g. overnight) and not being prepared for a rotation. 'At-gate, turnaround' refers to *all* time spent at-gate during the operational day - i.e. both passive/slack time and active handling between rotations (see also Annex I). The landing/take-off (LTO) cycle includes initial climb and (final) approach. 'Arrival management' encompasses all delays induced in TMAs, including holding in stacks and linear holding. The rest of the airborne phase is classified as 'en-route'.

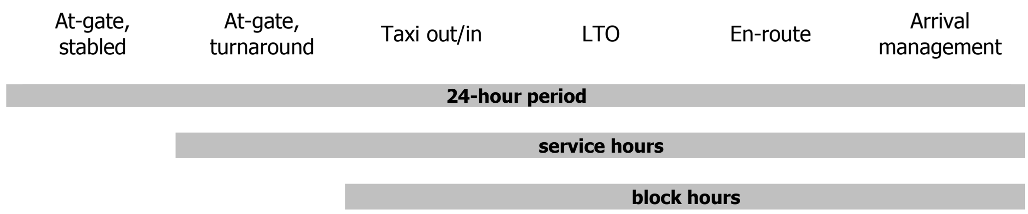


Figure 1. Flight phases and basic definitions

1.1.4 Block hours are defined as the time spent off-blocks (between gates), also referred to as aircraft 'utilisation'. Service hours are defined as the total time spent in service during the operational day, i.e. block hours plus 'active' time spent at-gate between rotations (excluding stabled time).

1.1.5 For conciseness, where previous work has been published, summaries are made and key references given, rather than reproducing the work. Updates to produce 2010 Euro-values are explained in full. Some sections, which present new work (e.g. Section 3.7 on reactionary costs) are more detailed than those summarising existing work.

1.1.6 All costs are for the year 2010 and are assigned values under three cost scenarios: 'low', 'base' and 'high'. These scenarios are designed to cover the likely range of costs for European operators. The 'base' cost scenario is, to the greatest extent possible, designed to reflect the typical case. Calculations are undertaken for the same twelve, core aircraft supported in earlier work [1]: B733, B734, B735, B738, B752, A319, A320, A321, AT43, AT72, B744, B763 (see Table B1 to decode designations). These are chosen both for representativeness of European movements and as a cross-section of operational costs.

1.1.7 The cost of delay is calculated separately for strategic delays (those accounted for in advance, for example likely to be reflected in the airline schedule) and tactical delays (those incurred on the day of operations, and not accounted for in advance). Links between the corresponding, dedicated sections are made in the text, where appropriate. Some tactical costs are derived (in part) from the strategic costs as initial starting points.

1.1.8 Tactical delay costs are scaled up to the network level because 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).

1.1.9 The total, *per-minute* tactical costs of delay increase as a function of the length of the delay, due to the passenger costs. This effect is further complicated by the reactionary costs. For the tactical costs of delay, the total costs and the passenger costs are therefore tabulated by delay duration. The strategic *per-minute* costs of delay do not increase as a function of delay duration and are not tabulated by different delay durations.

1.1.10 It seems likely that the percentage of flights delayed by more than 15 minutes will continue to be used in future as a key indicator for target setting. (It is noted that SESAR D5 [2] currently proposes that ≤ 3 mins late is 'on time'.) Delay costs are cited for the following delay durations: 5, 15, 30, 60, 90, 120, 180, 240 and 300 minutes.

1.1.11 Section 4 offers guidance on how to use the costs derived in this report. The costs calculated are appropriate for multiplying over substantial periods of time or a network, to give aggregate costs of delay. The passenger 'soft' cost of delay, a tactical cost associated with passenger market share, needs to be treated specially in the aggregate context. This is discussed in Section 3.6.20. Other costs are not affected in this way.

1.1.12 Section 5 outlines key opportunities for further study. This focuses on passenger delay cost estimations and reactionary cost models.

1.2 Current exceptions

1.2.1 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 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. Estimates of future emissions costs are not included in this report. These could readily be added to future versions of these calculations.

1.2.2 Variable Cost Index settings in the FMS are not considered in the fuel burn calculations (see also Annex F). These could also be added to future versions of these calculations. The issue of accelerated fuel burn to recover delay is raised in Section 5.

1.2.3 Marginal airport charge costs of delay have been ignored, since previous work [1] showed these to make a very small contribution to overall costs of delay.

1.2.4 Detailed/quantitative commentaries on SESAR performance targets are not included. This would be a particularly interesting area of future work (see also Section 5).

1.2.5 These calculations refer to passenger operations and the delay costs are often dominated by passenger costs to the airline. The cost of delay associated with airfreight and freighter operations has not been included and remains an opportunity for future research.

1.2.6 The cost of cancellations have not been included, although they have been compared (see sections 3.7.14 and 3.7.22) with the capped reactionary costs used, and are discussed further in Section 5.

2 Strategic cost of delay

2.1 Overview of calculations

2.1.1 Strategic delay costs are those which are anticipated and accounted for in advance. The strategic cost of delay is estimated through the cost of adding buffer to the airline schedule. In Annex K, the elasticity of cost with respect to output has been considered in this context. As a result, the unit costs for the high cost scenarios are moderately increased to reflect potential diseconomies of scale when adding buffer. Low and base scenario costs are not adjusted: planning to use 10% extra of an output (e.g. aircraft maintenance) increases this cost by 10%.

2.1.2 It is assumed that the amount of buffer to be used throughout the schedule is yet to be decided, whereas the number of cycles (rotations) on a particular airport-pair for a given day and season has already been decided. This does not mean that the number of cycles *per aircraft* is fixed, nor the service hours. We are still allowing extra buffer to consume extra resources (including crew time).

2.1.3 Fleet costs refer to the full cost of fleet financing, such as depreciation, rentals and leases of flight equipment. They implicitly include stand-by/spare aircraft (owned or leased).

2.1.4 Strategic costs are calculated for three phases: at-gate (APU and engines off), taxi and en-route (cruise/route extension). Since it would be exceptionally unusual to plan arrival management as a schedule buffer, it is not costed strategically. Although it is not practice to use taxi time as a buffer or flow-management tool in Europe, we have costed this phase for comparative purposes. Even in Europe today, schedule decisions could influence the amount of planned taxi time for a given route.

2.1.5 Strategic costs and tactical costs are not independent. If no buffers were used, the reactionary costs (multipliers) would increase markedly and the tactical costs would be significantly larger. Such dependencies are not modelled, although it is to be borne in mind that the calculations are thus based on the current equilibrium of typical European operations and on the 'fixed-cycles' assumption (Section 2.1.2, above). For a fuller exploration of such issues, including robust scheduling, see [49].

2.1.6 Ball et al. [21] report on an FAA-sponsored study 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[1] 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. See also Annex I.

[1] Costs to passengers are also calculated (see Annex C) as are wider costs such as the macro-economic impacts of direct costs.

2.2 Fuel

2.2.1 Currently, neither emissions costs (see Section 1.2.1) nor variable Cost Index settings in the FMS (see Section 1.2.2) are considered[2]. Nor are the effects of hedging, tankering, or weather, on rates of fuel burn or fuel costs. We have calculated the cost of fuel burned per minute for all three off-gate phases, and use the same values for strategic and tactical cost calculations.

2.2.2 Rates of fuel burn and fuel costs have to be taken into account for the three off-gate phases. The at-gate calculations assume the engines and APU are off. The fuel burn rates are given in **Annex F**. For the three cost scenarios, the into-plane costs of fuel (Jet A1) used are:

Table 1. Cost of fuel

Scenario	Cost of fuel / kg (Euros)
High	0.8
Base	0.6
Low	0.4

Source: 'Rotterdam' (Amsterdam-Rotterdam-Antwerp) Spot Prices [47].
High, 2008 average; low, 2009 minimum.
Mid-range taken as base (Note: 2009 average, 0.55 [2dp])

2.2.3 Each airline has a company fuel policy applied when planning flights. There are legal requirements covering the minimum fuel uplift, which may vary between states and regions. However, fuel regulations[3] laid out in EU-OPS 1 [43], regarding common technical requirements and administrative procedures, take precedence in Europe. The minimum fuel requirements, which include arrival management holding, comprise: taxi fuel; trip fuel (to cover climb, cruise, descent, approach and landing); contingency fuel (5% of trip fuel as a reserve); alternate fuel (to cover flight to the alternate aerodrome as a reserve) and final reserve fuel (to cover 30 minutes holding at the alternate aerodrome as a reserve). Extra fuel may additionally be carried at the discretion of the commander.

2.2.4 **Fuel carriage penalty.** Carrying fuel from the origin to its point of consumption, in itself gives rise to an additional fuel burn, known as a fuel carriage penalty. As a simplifying assumption, we have applied this only to arrival management (e.g. whereby fuel burned in a holding pattern at the destination incurs an additional fuel burn in carrying that fuel *to* the destination TMA). We have adopted the *Assumed Percentage Burn-off* method and assume a fuel carriage penalty of 4% per flight-hour (Boeing [44] suggest 4-5%). See also Table F3 (Annex F).

[2] Although the issue of accelerated fuel burn to recover delay is raised in Section 5.
[3] EU-OPS 1 replaces JAR-OPS 1 (Joint Aviation Requirements); refer to Section OPS 1.255: Fuel Policy.

2.3 Maintenance

2.3.1 For strategic costs, we first require the cost per block hour. Although these costs are not published for European aircraft, 2002 unit costs have been previously modelled [1] for the twelve supported aircraft types. These values (Table 2) were largely based on detailed data collected through interviews with eight European airlines, selected to give a good range of block-hour costs.

Table 2. Maintenance costs per block hour (2002)

Aircraft	Low scenario	Base scenario	High scenario
B733	380	740	940
B734	440	790	980
B735	380	680	840
B738	320	610	890
B752	500	890	1 110
B763	610	1 140	1 660
B744	1 260	1 610	1 800
A319	400	790	990
A320	410	720	1 030
A321	480	850	1 060
AT43	210	380	470
AT72	260	470	570

All costs are Euros per block hour (2002) and include overheads.

2.3.2 For a given airline, these costs may change considerably over one or two years, due to changes in the age or composition of aircraft fleets, airline takeovers, or changes in lease-associated maintenance[4]. Several aircraft may require a very expensive 'heavy' maintenance visit in the same financial year. Maintenance might be centralised within an airline group, outsourced more, or accounted for in a different way.

2.3.3 From 2002 to 2008 (the latest year for which ICAO data are available, [7]), some annual maintenance costs rose sharply, whilst others had periods of large falls. It is better to estimate changes over longer rather than shorter periods of time and using several airlines' data, due to annual fluctuations possible within a given airline.

2.3.4 Figure 2 shows cleaned ICAO [7] fleet-wide block-hour costs (submitted in USD, exchange rates in Annex E). All non-freighter-only European airlines submitting data in a given year are included. The solid black curve shows the mean block-hour cost. The upper and lower bands show twice the standard error of the mean (SEM). On the left is the mean of the base values in Table 2, weighted by the corresponding total flights of Table B3; the error bars are the corresponding low and high cost scenarios.

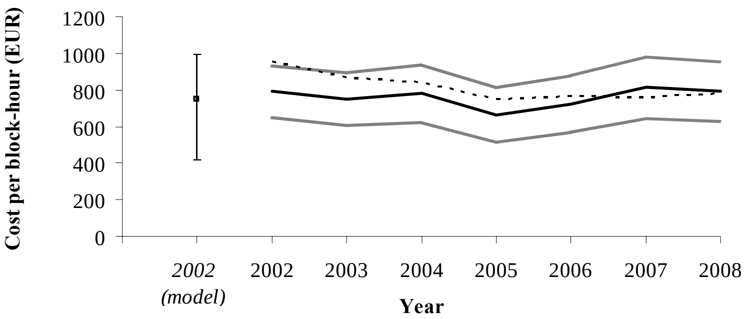


Figure 2. Trends in maintenance block-hour costs 2002-2008

[4] Ryanair's total maintenance cost increased around 30% over the summer of 2009 due to an increase in leased aircraft.

2.3.5 The grey bands show that the dispersion of block-hour values is fairly similar in each year from 2002 to 2008, albeit with a general trend of slight widening. Our objective is to capture a reasonable spread across the scenarios, excluding individual values which are too extreme or erratically reported by airlines.

2.3.6 The modelled costs in 2002 (left of figure) show quite a low minimum value. Nevertheless, a large operator of narrowbodies reported a value in 2008 (consistent with its previous reporting) 15% lower than these 2002 modelled narrowbody values.

2.3.7 The block-hour weighted mean (dashed black curve) follows the unweighted average (solid black curve) reasonably closely. The 2008 unweighted mean is exactly the same as the 2002 unweighted mean[5]. We have therefore adopted the 2002 values as the 2008 values, with the exception of a narrowbody adjustment[6]. The 2008 values need to be finally adjusted to estimates for 2010.

2.3.8 ICAO data beyond 2008 are 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. Air France (consistently much higher than ICAO average) - KLM (missing ICAO data) reported a net fall[7] of 5% over the summer of 2009 (financial report, November 2009). For the twelve months preceding September 2009, easyJet (consistently rather lower than ICAO average) reports an increase of 10% in total maintenance spend. Finnair (typically higher than ICAO average) reports an increase of 13% for the nine months preceding September 2009. British Airways (converging year-on-year towards ICAO average; almost equal in 2008) reports a 1.2% increase in total spend over the summer of 2009.

2.3.9 The mean upward trend from 2005 to 2007, ceases for 2007 to 2008 (Figure 2). Limited data since 2008 suggest some upward and some downward changes. We have adopted a small increase of 5%, across all scenarios and aircraft types, for 2008 to 2010. This produces the new *block*-hour unit costs for 2010.

2.3.10 The strategic cost of delay is estimated through the cost of adding buffer to schedule. In Annex K, the elasticity of cost with respect to output has been considered in this context. As a result, the unit costs for the high cost scenarios are moderately increased to reflect potential diseconomies of scale associated with adding buffer to schedule. Low and base scenario costs are not adjusted for use in the strategic cost calculations.

2.3.11 A proportion of these *block*-hour costs then needs to be redistributed back over the at-gate phase (at-gate *turnaround* phase only[8]). They are allocated in the same per-minute cost ratios (summarised in Figure 3) as the at-gate:taxi:airborne tactical per-minute costs and in respect of the amount of time each aircraft type spends in each phase. (The derivation of the tactical maintenance costs is presented in Section 3.3.)

[5] Weighting the values by block hours results in a greater relative representation of larger airlines and longer-hauls. We have favoured unweighted values in this context for better capture of airline-to-airline differences. Whilst the weighted block hours show a 20% fall from 2002 to 2007, there is practically no change (2% increase) from 2007 to 2008. Airline Monitor [8] report average block-hour costs, differentiated as narrowbody and widebody aircraft, both having increased by 7% from 2002 to 2008 (in US Dollars).

[6] The 2008 narrowbody ***low*** cost scenarios were reduced by 10%, to take account of the large airline referred to in the previous section.

[7] CSA's block-hour maintenance costs decreased by 2% in the period 2006 to 2008 [7].

[8] We make the approximation that the stabled (inactive) time at-gate has no associated maintenance costs. See Section 1.1.3 for definitions.

2.3.12 The remaining block-hour costs are finally allocated across the taxi and airborne phases. They are also allocated in the same ratios as the at-gate:taxi:airborne tactical costs (Figure 3) and in respect of the amount of time spent in each phase.

2.3.13 As with the *tactical* maintenance costs[9], separate airborne maintenance costs for cruise and arrival management are not allocated, since these would produce very similar results. A common 'airborne' value is assigned.

2.3.14 Figure 3 summarises the strategic cost calculation. The *ratios* of the at-gate: taxi:airborne per-minute costs are shown at the top of the figure. The results of these calculations are tabulated in tables 3 - 5.

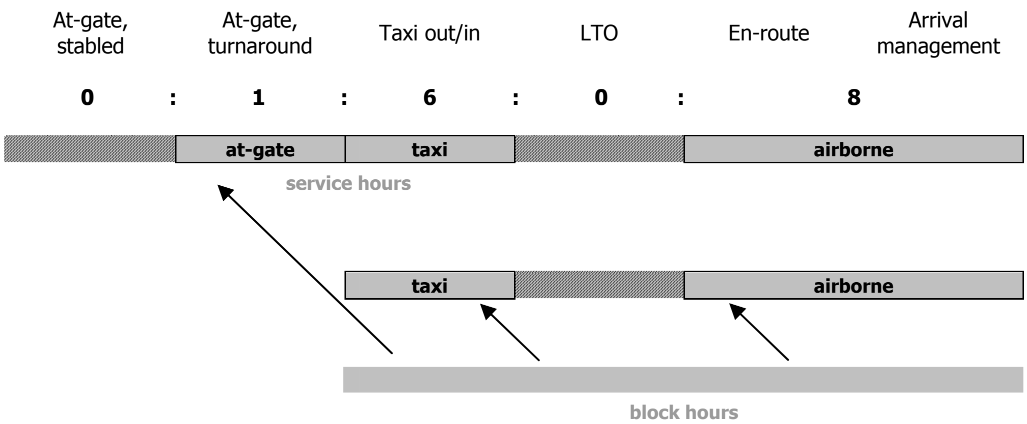


Figure 3. Assigning block-hour maintenance costs across appropriate phases
Note. Cost ratios are rounded here. Very similar values resulted for each aircraft type.

Table 3. At-gate, strategic maintenance costs

Aircraft	Low scenario	Base scenario	High scenario
B733	40	100	150
B734	50	100	160
B735	40	90	140
B738	40	80	150
B752	60	120	190
B763	90	160	290
B744	170	220	320
A319	50	100	170
A320	50	100	180
A321	60	120	180
AT43	20	40	70
AT72	30	50	90

All costs are Euros per hour (2010) and include overheads.

9 Unlike the tactical fuel burn calculations.

Table 4. Taxi, strategic maintenance costs

Aircraft	Low scenario	Base scenario	High scenario
B733	260	570	910
B734	310	610	970
B735	270	540	850
B738	220	470	890
B752	360	720	1 140
B763	490	910	1 700
B744	990	1 260	1 800
A319	280	600	970
A320	300	580	1 070
A321	340	670	1 050
AT43	150	310	490
AT72	180	370	580

All costs are Euros per hour (2010) and include overheads.

Table 5. Airborne (en-route), strategic maintenance costs

Aircraft	Low scenario	Base scenario	High scenario
B733	340	740	1 200
B734	400	790	1 250
B735	340	680	1 080
B738	290	620	1 160
B752	450	900	1 430
B763	630	1 170	2 180
B744	1 290	1 640	2 330
A319	370	800	1 290
A320	380	740	1 350
A321	440	880	1 390
AT43	170	350	550
AT72	220	430	680

All costs are Euros per hour (2010) and include overheads.

Airborne maintenance costs commonly apply to en-route and arrival management phases, although strategic arrival management costs are not presented in this report (see Section 2.1).

2.3.15 All of these costs have been calculated such that when they are multiplied by the time each aircraft type spends in each phase (see Table B1), the original unit cost is obtained. This is another aspect in which the costs calculated partly reflect the current equilibrium of operational practice (as raised in Section 2.1).

2.3.16 The at-gate costs (Table 3) are relatively low (compared to the other phases) because, as discussed, relatively little wear and tear on the airframe is experienced at-gate and the engines are off for the vast majority of this time (which we have approximated to be all of the at-gate time).

2.3.17 The derivation of the tactical maintenance costs, following a number of the principles of this section, is presented in Section 3.3.

2.4 Fleet

2.4.1 'Fleet' costs refer to the full cost of fleet financing, such as depreciation, rentals and leases of flight equipment. Since utilisation has only a very small effect on these costs [1], they are wholly allocated to the strategic phase and the corresponding tactical delay costs are thus taken to be zero. These costs are determined by service hours (as defined in Section 1.1.4).

2.4.2 Although these costs are not published for European aircraft, 2002 unit costs have been previously modelled [1] for the twelve aircraft types in Table 6.

Table 6. Fleet costs per service hour (2002)

Aircraft	Low scenario	Base scenario	High scenario
B733	280	470	660
B734	350	580	810
B735	310	520	730
B738	440	730	1 030
B752	450	740	1 040
B763	600	1 000	1 400
B744	960	1 600	2 240
A319	420	690	970
A320	450	760	1 060
A321	550	910	1 270
AT43	150	240	340
AT72	200	330	460

All costs are Euros per service hour (2002).

2.4.3 The model captured these typical, full fleet costs, based on monthly operating lease rates, which, in turn, are strongly dependent on aircraft values. Values were sourced from airline interviews, literature and Airclaims data. These sources were consolidated with adjustments made for market conditions and lessors' profit margins[10]. Typical aircraft utilisation and turnaround times enabled fleet costs to be expressed per service hour.

[10] The basic (refined in [1]) value was 20% in 2002, and still applicable in November 2009 [9].

2.4.4 Figure 4 shows cleaned ICAO [7] fleet costs per *block* hour (submitted in USD, exchange rates in Annex E). All non-freighter-only European airlines submitting data in a given year are included. These are based on the following operating expenses as reported in ICAO data: 'rental of flight equipment' (flight operations subcategory); 'depreciation – flight equipment', 'amortization of capital leases – flight equipment' and 'other' (depreciation and amortization subcategory). We cannot determine exactly how airlines allocate these costs (although different airlines appear to use different (sub)categories for the same costs), but we take the *sum* of these high-level costs to cover the full cost of fleet financing.

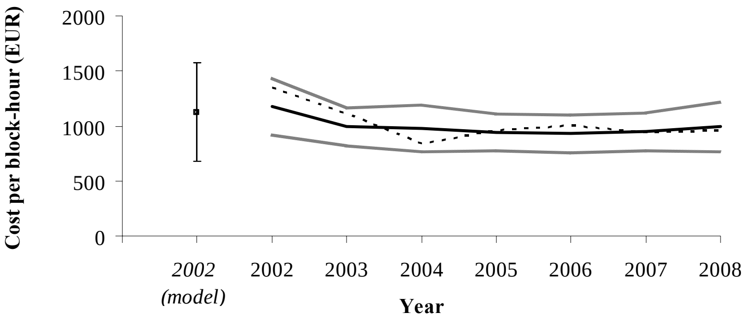


Figure 4. Trends in fleet block-hour costs 2002-2008

2.4.5 The values in Figure 4 are plotted per *block* hour since they are derived from the ICAO data as reported, avoiding the need to estimate service hours for each year. The solid black curve shows the mean cost. The upper and lower bands show twice the standard error of the mean (SEM). On the left is the mean of the base values in Table 6 (adjusted to block hours), weighted by the corresponding total flights of Table B3; the error bars are the corresponding low and high cost scenarios.

2.4.6 The 2008 unweighted mean is **15% lower** than the 2002 unweighted mean[11]. The unweighted mean is also closer to the 2002 modelled value (<5% difference) than the block-hour weighted mean (dashed black curve). In 2008, both the unweighted mean and the weighted value are within 4% of each other.

2.4.7 Other (more limited) data support the association (modelled in [1]) between these consolidated ICAO total fleet costs and aircraft values *per se*. For example, comparing 'Classic' Boeing narrowbody values for 2002 [38] and 2008 [9] also shows a **15% reduction** overall. Comparing adjusted Airclaims valuations for 2002 of our twelve aircraft and the corresponding 2008 values (jets, April; turbo-props, June; [9]) shows a 13% reduction.

2.4.8 As a first step, we thus set the 2008 values at 15% lower than the 2002 values.

2.4.9 However, several large European airlines reduced their block-hour fleet costs from 2002 to 2008 by 50%. Two of these (both narrowbody operators) reported values in 2008 (consistent with previous reporting) which were still lower than the 2002 narrowbody values, after the 15% reduction. Several other airlines had similarly low values (consistent with previous reporting) in 2008. In addition to these ICAO data, average lease rates (including widebodies) fell from 2002 (adjusted Airclaims data) to 2009/2010 [9] by just over 40%.

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[11] Weighting the values by block hours results in a greater relative representation of larger airlines and longer-hauls. We have favoured unweighted values in this context for better capture of airline-to-airline differences. In fact, the block-hour weighted mean follows the unweighted average reasonably closely, especially in the later period. Whilst the weighted block hours show a 30% fall from 2002 to 2005, there is practically no change (1% increase) from 2005 to 2008.

2.4.10 The 2008 ***low*** cost scenario was thus set at 50% of the 2002 values for all aircraft to capture these low values in the scenario range. This results in quite a large high-low range, reflecting the source (ICAO) data. Base and high cost scenarios for 2008 were adopted at 15% lower than their corresponding 2002 values.

2.4.11 The last few years have seen a continued and increased downward trend in new and used aircraft values and lease rates. With less capacity required, airlines have stored aircraft and deferred or cancelled new deliveries from manufacturers.

2.4.12 Although ICAO data are not available at the time of these calculations for beyond 2008, the 2008 values need to be finally adjusted to estimates for 2010. Although Figure 4 shows quite flat curves from 2005 to 2008, recent aircraft market valuations demonstrate a sharp decrease. "Widebodies and narrowbodies, new and old are equally affected … values have now fallen at a rate unseen for many years" [40].

2.4.13 Comparing minimum/maximum averaged aircraft valuation differences between 2008 and the latest values available[12], narrowbody jet values decreased on average by 25% – 29% ([9], [39]; supported by [40]); widebodies decreased by 31% – 40% ([39], [9]); turboprops by 6% – 10% ([39], [9]). Lease rates typically fall and recover before aircraft values. They are expected to increase in 2010, followed by aircraft values in 2011. Many operators are already locked into previous, long-term agreements. Allowing for some anticipated recovery, we have taken half of the average percentage falls for these aircraft types, and rounded them to the nearest 5%, to produce final adjustments to the 2008 values to produce 2010 estimates (with an element of future proofing). 20% (widebodies), 15% (narrowbody jets) and 5% (turboprops) is thus removed from the 2008 values to produce 2010 estimates

2.4.14 To reflect potential diseconomies of scale associated with adding buffer to schedule, as described in Annex K, the high cost scenarios are moderately increased. Low and base scenario costs are not adjusted. Finally converting these block-hour values to service-hour values, using the data of Table B1, the results are as given in Table 7. The 2010 base scenario values are 20-35% lower than the 2002 values.

Table 7. Fleet costs per service hour (2010)

Aircraft	Low scenario	Base scenario	High scenario
B733	110	320	540
B734	130	380	640
B735	130	360	610
B738	190	540	920
B752	200	560	950
B763	250	710	1 210
B744	390	1 090	1 860
A319	180	510	870
A320	210	610	1 030
A321	260	730	1 240
AT43	60	160	280
AT72	80	230	390

All costs are Euros per service hour (2010).
These costs commonly apply to all phases of service hours.

[12] 2008 values as per Section 2.4.7. Latest jet values October 2009 and June 2009 for turboprops (ATR 42-/72-500 used by [39]). Data supplied by The Aircraft Value Analysis Company (in [9]) and Ascend V1 (in [39]).

2.5 Crew

2.5.1 The strategic crew costs are also derived from block-hour costs. Typical pilot and flight attendant salaries have been calculated [5] in 2008 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.

2.5.2 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 calculations of Section 3.6). Abnormal aircraft seat configurations were excluded from this range.

2.5.3 A detailed examination was undertaken [5] of payment mechanisms for aircraft crew [32], with reference to salary ranges in 2008. In Europe, airlines typically pay crew fixed salaries, supplemented by (relatively) small flying-time payments and (cycles-based) allowances. (Crew in North America are typically remunerated by a 'pay-and-credit' scheme whereby duty and flying time determine the salary.)

2.5.4 The calculations in this report 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 [33]. 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.

2.5.5 To update the 2008 strategic crew costs to 2010 values, pay deals since 2008 for ten European airlines have been considered. Removing outliers, for cabin crew these have been typically around 5%, with slightly higher values for captains and first officers (6-7%). Examining these (confidential) data from various sources, a value of 5% across all crew was a good working average and also the median value. There were no clear trends by aircraft type. We have thus applied this increase across all crew, aircraft types and scenarios for 2008 to 2010. This produces the new block-hour unit costs for 2010.

2.5.6 As with the maintenance costs, a proportion of these *block*-hour costs then needs to be redistributed back over the at-gate phase, to produce common (ground or airborne), *service*-hour costs. (If simple block-hour rates were multiplied by at-gate hours too, the total monthly/annual crew cost would be too high.) Some overtime is allowed for in the base and high cost scenarios, in each case based on the corresponding basic salaries. Lower amounts of overtime per average service hour are assigned to the strategic phase, compared with the tactical costs.

2.5.7 Finally, to reflect potential diseconomies of scale associated with adding buffer to schedule, as described in Annex K, the high cost scenarios are moderately increased. Low and base scenario costs are not adjusted. The resulting values for the common service-hour crew costs are presented in Table 8.

Table 8. Crew costs per service hour by aircraft type (ground or airborne)

Aircraft	Low scenario	Base scenario	High scenario
B733	190	330	570
B734	190	320	570
B735	160	310	560
B738	210	400	720
B752	280	420	700
B763	400	680	1 310
B744	510	870	1 660
A319	200	310	530
A320	210	360	620
A321	240	370	630
AT43	100	160	270
AT72	110	180	320

All costs are Euros (2010). On-costs included. Base and high scenarios with overtime.

2.6 Passenger

In practice, some contingency for passenger delay is invested in operations at the strategic phase, e.g. by having additional staff at airports to manage them. These contingencies would generally be less necessary as schedule buffer is increased. At present, we are not aware of any data on this and any corresponding estimate would be rather ill-informed.

Whilst a separate study could be launched to investigate these, it is probably the case that to a significant extent, the economic downturn has caused airlines to reduce these costs to a minimum (e.g. by requiring *in situ* staff to deal with such delayed passengers along with others, and as a general part of customer service and transfer desk duties). These costs are not assessed in these calculations.

2.7 Reactionary costs

Reactionary costs refer to 'knock-on' effects in the network, on the day of operations. They are not costed in the strategic phase, in the sense that schedules (for example) are actually designed at the strategic phase with sufficient resilience to avoid tactical delay. (However, buffers may result in 'schedule delay' - a term used to describe the difference between a desired departure (or arrival) time and the closest option (realistically) available to the passenger [14]. This is a 'value of time' cost to the passenger: see also Annex C.) The extent to which this resilience fails on the actual day is captured as the tactical delay costs presented in the next section.

2.8 Tabulations of total strategic costs

As explained in Section 2.1, strategic costs are reported for three phases: at-gate, taxi and en-route. These are tabulated in the following three tables. The costs are derived by summing the fuel costs (see Section 2.2 and Annex F; does not apply at-gate), the at-gate / taxi / en-route maintenance costs (Section 2.3) and the service-hour costs for fleet (Section 2.4) and crew (Section 2.5). There are no strategic passenger costs or reactionary effects. Section 4 discusses the use of these costs.

At-gate cost changes. Overall, the at-gate strategic costs have fallen since the earlier report (2004, [1]). Pressures on costs and utilisation have contributed to this. The considerable fall in fleet costs was discussed in Section 2.4; these comprise around 45-60% of the at-gate base scenario costs. The 2010 block-hour crew costs have also decreased (although some only slightly). For European airlines reporting crew costs to ICAO in 2002 and 2008, there was an average decrease per block hour over this period (costs weighted by airline block hours; Air France excluded due to an atypically large reported increase). Furthermore, crew costs are more accurately assigned to service hours in the 2010 model. Crew costs comprise around 30-45% of these at-gate costs. Although block-hour maintenance costs have increased over this period, the increase is small (see Section 2.3) and the proportional contribution is small (10-15%). These non-fuel strategic costs have thus fallen overall.

En-route cost changes. Fuel costs comprise the largest proportion of the 2010 base scenario en-route costs for widebodies (averaging around 60%) and for the narrowbody jets (50%). The next largest contribution is maintenance costs (around 20% and 25%, respectively). For the turboprops, this order is reversed: 30% fuel; 35% maintenance. As an upward driver of en-route costs, the cost of fuel has doubled since the earlier reporting. The net results are: from no change, to around a 10% increase, for the narrowbody jets; a larger increase for the widebodies (around 15-20%); decreases (15-20%) for the turboprops (smaller fuel proportion, decreased crew and fleet costs).

Table 9. AT-GATE total strategic costs

Aircraft	Low scenario	Base scenario	High scenario
B733	340	740	1 260
B734	370	800	1 380
B735	340	760	1 310
B738	440	1 020	1 790
B752	540	1 100	1 850
B763	740	1 550	2 810
B744	1 070	2 180	3 830
A319	430	930	1 570
A320	480	1 070	1 830
A321	550	1 210	2 050
AT43	180	360	620
AT72	220	470	800

All costs are Euros per hour (2010).

Table 10. TAXI total strategic costs

Aircraft	Low scenario	Base scenario	High scenario
B733	890	1 710	2 680
B734	980	1 850	2 900
B735	920	1 740	2 730
B738	950	1 900	3 170
B752	1 360	2 480	3 830
B763	1 760	3 220	5 440
B744	3 030	4 940	7 610
A319	930	1 840	2 940
A320	1 100	2 110	3 450
A321	1 160	2 260	3 580
AT43	430	810	1 280
AT72	520	1 000	1 580

All costs are Euros per hour (2010).

Table 11. EN-ROUTE total strategic costs

Aircraft	Low scenario	Base scenario	High scenario
B733	1 620	2 850	4 260
B734	1 680	2 940	4 400
B735	1 520	2 690	4 030
B738	1 730	3 100	4 850
B752	2 250	3 870	5 730
B763	3 170	5 390	8 470
B744	6 100	9 480	13 700
A319	1 670	3 000	4 540
A320	1 750	3 120	4 880
A321	2 050	3 650	5 490
AT43	500	920	1 440
AT72	660	1 220	1 900

All costs are Euros per hour (2010).

3 Tactical cost of delay

3.1 Overview of calculations

This section presents the calculation of the tactical cost of delay for four phases: at-gate (APU and engines off), taxi, en-route (cruise/route extension) and arrival management (e.g. flow sequencing, stacking). These costs are dominated primarily by passenger costs, and then fuel burn differences. Tactical costs are marginal costs, incurred on the day of operations. Some tactical costs are derived (in part) from the strategic costs (see previous section) as initial starting points, whereas the strategic and tactical fuel costs are the same.

3.2 Fuel

3.2.1 Fuel costs and burn rates were introduced in Section 2.2. Burn rates are tabulated in Annex F. The same values have been used for both the strategic and tactical calculations.

3.2.2 Currently, neither emissions costs (see Section 1.2.1) nor variable Cost Index settings in the FMS (see Section 1.2.2) are considered, although the issue of accelerated fuel burn to recover delay is raised in Section 5.

3.3 Maintenance

3.3.1 The marginal (tactical) 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. Large proportions of maintenance costs are fixed, in terms of overheads, or on a per-cycle basis. The basic principle of these calculations is to estimate marginal, time-based costs from unit costs. This is achieved by removing the appropriate fixed costs and apportioning the remaining costs across marginal delay minutes.

3.3.2 Appropriately assigning per-minute marginal costs requires an understanding of how unit costs are distributed as a function of flight hours (FH) and flight cycles (FC), differentiating the former from block hours. For modern aircraft types, 'letter check' maintenance distinctions are less prevalent, since tasks are now 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. Below are the typical maintenance check intervals for 'A' and 'C' checks, whereby the newer 'phase' intervals have been converted to letter check intervals.

Table 12. Typical maintenance check intervals

Aircraft	'A' Check	'C' Check
B733	275 FH	18 months
B734	275 FH	18 months
B735	275 FH	18 months
B738	500 FH	4000-6000 FH
B752	500-600 FH	18 months / 6000 FH / 3000 FC
B763	600 FH	18 months / 6000 FH
B744	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
AT43	300-500 FH	3000-4000 FH
AT72	300-500 FH	3000-4000 FH

Key: FC, flight cycles; FH, flight hours.

3.3.3 Such data (above) have been used to inform these calculations (see also Section 3.3.10). To derive the marginal costs the overheads (40% [6]) are first removed. A gate-to-gate model has been developed [1] whereby the remaining maintenance cost is apportioned between the airframe/components (65%) and powerplants (35%), then distributed across flight phases. The distributions of costs are based on (expert) judgement [1] and feedback ([36], [37]).

3.3.4 50% of the airframe/components and 60% of the powerplant costs are allocated to the LTO cycle as fixed, purely per-cycle costs and thus also excluded from the cost allocation (as re-capped below).

3.3.5 Throughout the models, fuel burn rates (see Annex F) are used as a proxy for engine workload to apportion the powerplant costs across the phases. Separate airborne maintenance costs for cruise and arrival management are not allocated, since these would produce very similar results. A common 'airborne' value is assigned. (Fuel costs *per se* are calculated separately for cruise and arrival management - see sections 2.2 and 3.2).

3.3.6 **LTO cycle.** A high share of the total wear and tear is experienced in the high intensity phases of the LTO cycle. It is assumed that the number of cycles does not vary as a function of delay and these costs are excluded from the cost allocation. It is also assumed that no delays occur during this high intensity phase.

3.3.7 **Taxi and airborne.** For these off-block phases of flight the remaining airframe and components costs are allocated equally. The powerplant costs are allocated across these phases according to engine workload. The costs are also allocated such that when they are weighted by the corresponding time spent in each phase (see Table B1), the original average off-block value is obtained.

3.3.8 **At-gate turnaround.** For turnaround (see Section 1.1.3 for definitions), 20% of the *off-block* airframe and components cost per hour is judgementally assigned[13] and zero powerplant costs (powerplants are assumed to be off at-gate). No costs are assigned for at-gate stabling (a very low value could be assigned, but this would make little difference to the calculations).

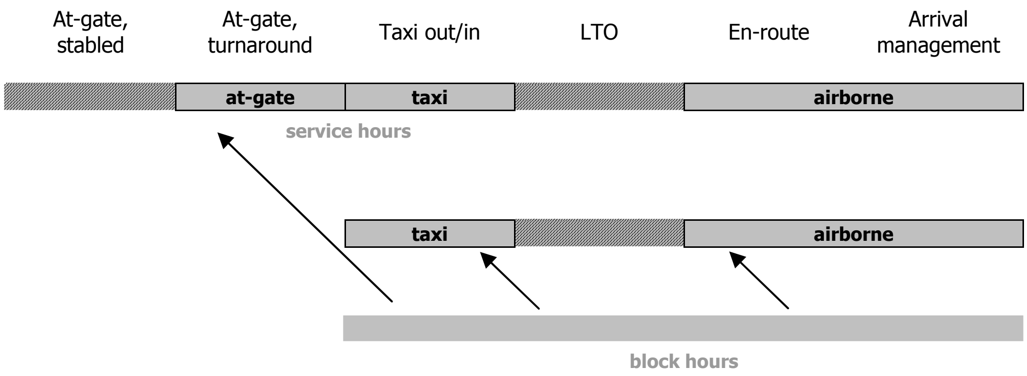

Figure 5. Assigning tactical maintenance costs across appropriate phases

3.3.9 The results of these calculations are given in tables 13 - 15. All of these costs have been calculated such that when they are multiplied by the time each aircraft type spends in each phase (see Table B1), the original aggregate cost is obtained. The relatively low at-gate costs are explained in Section 2.3.16.

Table 13. At-gate, tactical maintenance costs (per minute)

Aircraft	Low scenario	Base scenario	High scenario
B733	0.2	0.4	0.6
B734	0.2	0.5	0.6
B735	0.2	0.4	0.5
B738	0.2	0.4	0.6
B752	0.3	0.6	0.7
B763	0.4	0.7	1.1
B744	0.8	1.0	1.1
A319	0.2	0.5	0.6
A320	0.2	0.4	0.6
A321	0.3	0.5	0.7
AT43	0.1	0.2	0.3
AT72	0.1	0.3	0.3

All costs are Euros (2010) per minute. Costs exclude overheads.

[13] The off-block costs are reduced to take the at-gate costs into account, so that the total costs remain the same.

Table 14. Taxi, tactical maintenance costs (per minute)

Aircraft	Low scenario	Base scenario	High scenario
B733	1.2	2.6	3.3
B734	1.4	2.9	3.5
B735	1.3	2.5	3.1
B738	1.0	2.2	3.2
B752	1.7	3.4	4.2
B763	2.3	4.2	6.2
B744	4.6	5.9	6.5
A319	1.3	2.8	3.5
A320	1.4	2.7	3.9
A321	1.6	3.1	3.8
AT43	0.7	1.4	1.8
AT72	0.9	1.7	2.1

All costs are Euros (2010) per minute. Costs exclude overheads.

Table 15. Airborne, tactical maintenance costs (per minute)

Aircraft	Low scenario	Base scenario	High scenario
B733	1.6	3.5	4.4
B734	1.9	3.7	4.6
B735	1.6	3.2	3.9
B738	1.4	2.9	4.2
B752	2.1	4.2	5.2
B763	2.9	5.4	7.9
B744	6.0	7.6	8.5
A319	1.7	3.7	4.7
A320	1.7	3.4	4.9
A321	2.1	4.1	5.1
AT43	0.8	1.6	2.0
AT72	1.0	2.0	2.5

All costs are Euros (2010) per minute. Costs exclude overheads.
Airborne maintenance costs commonly apply to en-route and arrival management phases.

3.3.10 The airborne values are fairly similar (cost ratios from 0.7 to 1.9) to literature-sourced values (not shown) for combined 'A' plus 'C' checks converted to average block-minute costs. The implication for those airlines using such 'A' plus 'C' check estimates for Cost Index calculations (see Section 1.2.2) is that these probably give not unreasonable estimates of the true marginal cost of maintenance.

3.4 Fleet

As explained in Section 2.4, fleet costs do not apply to the tactical phase.

3.5 Crew

3.5.1 The flight and cabin crew marginal costs are based on 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 flight and cabin crew, which produced the unit costs for 2010 presented in Section 2.5. For the tactical costs, the (cycles-based) allowances referred to in Section 2.5.3 are removed.

3.5.2 **Low cost scenario.** 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. Zero cost is thus assigned to the low cost scenario.

3.5.3 **High cost scenario.** It cannot be assumed that at-gate and off-gate hours do not generate additional costs to the airline for the base and high cost scenarios. Delay minutes are set at overtime rates for the high cost scenario.

3.5.4 **Base cost scenario.** 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 modelled for the base cost scenario, using derived 'time-based' salaries for flight and cabin crew, for each aircraft type.

3.5.5 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 proportionally spread over crew paid at basic and overtime rates.

3.5.6 The aircraft configurations of Table B2 and the corresponding crewing requirements are used to produce the marginal crew costs shown below. The low cost tactical scenario is set at zero. The costs apply to ground and airborne phases.

Table 16. Marginal crew costs per minute, ground or airborne

Aircraft	Low scenario	Base scenario	High scenario
B733	0	8.5	17.7
B734	0	8.2	17.8
B735	0	8.0	17.3
B738	0	9.0	19.5
B752	0	9.0	18.1
B763	0	12.9	34.6
B744	0	16.7	45.0
A319	0	7.3	15.2
A320	0	7.8	16.1
A321	0	7.8	16.1
AT43	0	5.6	11.5
AT72	0	6.1	13.0

All costs are Euros (2010) per minute. On-costs included.

3.6 Passenger

3.6.1 This report 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 this report. See Annex C for further discussion. A cost of passenger delay *to the airline* may be classified as either a 'hard' or 'soft' cost.

3.6.2 '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.

3.6.3 '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.

3.6.4 These costs have been previously [1] derived from independently concurring sources (two European airlines) on total passenger costs for a 2003 reference base. Since then, the European Union's air passenger compensation and assistance scheme (Regulation (EC) No 261/2004) has been introduced (17 February 2005). It affords passengers with additional rights in cases of flight disruption (denied boarding, cancellation and delay). It 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.

3.6.5 Longer passenger delays will tend to have higher *per-minute* 'hard' and 'soft' costs than shorter ones. Recently, changes to 'hard' [11] and 'soft' [14] passenger costs, and new models of their *distributions* as a function of delay duration, have been used to estimate costs for 2008. These both include an assessment of the impact of Regulation 261. These methods are summarised in this report, partially re-modelled, and used to produce costs for 2010.

3.6.6 'Hard' and 'soft' passenger costs of delay need to be translated into per-aircraft costs for each of the twelve supported aircraft. 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 was 80%.

Passenger hard costs

3.6.7 There is very little literature on actual passenger hard costs. Discussing disruption management, Kohl et al. [16] do not quote *specific* delay costs. Bratu and Barnhart [17] use values of time to estimate passenger costs. Jovanović [18] 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.

3.6.8 Using large data sets for passenger bookings and flight operations from a major US airline, Bratu and Barnhart [19] 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. Based on a model using 2005 US data, Sherry et al. [20] concur that "flight delay data is a poor proxy for measuring passenger trip delays".

3.6.9 In order to distribute the hard costs as a function of delay duration, an empirical (airline) source [18] of 'care' costs (meal vouchers, hotel accommodation, tax-free vouchers, frequent-flyer programme miles and phonecards) was combined [11] with a theoretical distribution of 'reaccommodation' costs (rerouting/rebooking passengers, ticket reimbursements and compensation).

3.6.10 As per Section 3.6.8, specifically-fitted, passenger-centric corrective weighting factors were used, with attention paid that neither care nor reaccommodation costs modelled were allowed to unduly dominate total values. The result is shown in Figure 6, by three scenarios.

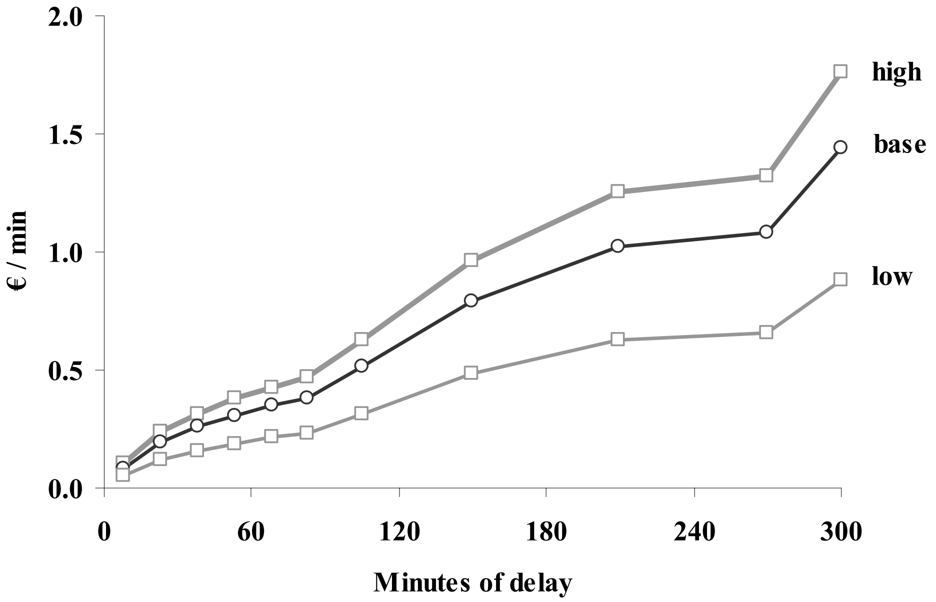

Figure 6. Passenger hard cost model by delay duration

Source: Adapted from [11].

3.6.11 Taking the data values used for Figure 6 [11], a power curve ($y=ax^b$) fit (Figure 7) can be derived to smooth some of the higher rates of change in cost per minute and to make automated calculations more tractable. (Although good *linear* fits may be obtained, these significantly underestimate costs in the range of less than one hour.) A substantial majority of delays occur at lower magnitudes (see Table B4), so it is particularly important that, as far as possible, these are not over- or under-estimated. It is also of particular importance that the cost at 300 minutes is well fitted, as this value is used in the capping of widebody rotational costs (see Section 3.7.22). For each scenario curve, the maximum deviation between the fitted values of Figure 7 and those of Figure 6, for the first two data points (8, 23 mins) and the last data point (300 mins), is 2%.

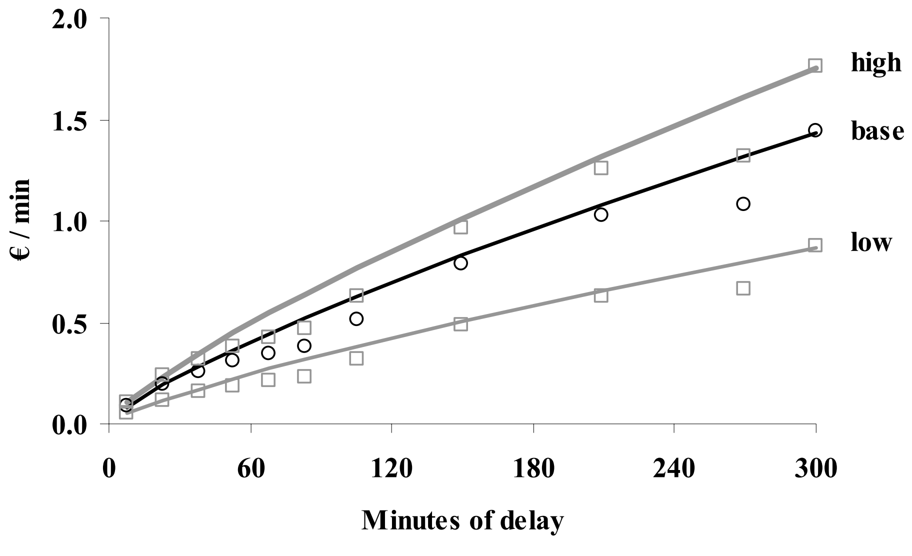

Figure 7. Power curve fit of passenger hard costs as a function of delay duration

3.6.12 Weighting the differences for each data point, along each curve, by the proportion of delays in Table B4 (2007 values used for consistency) gives total increases (new fit c.f. [11]) from 0.9% (low scenario) to 1.5% (high scenario). Small additional increments have been used (scenario specific) to give a net compound inflationary increase for 2008 to 2010 of 1.81% (see Annex E). The base scenario weighted average is EUR 0.183 (per passenger, per minute). The values below are quoted by the delay magnitudes introduced in Section 1.1.10.

Table 17. Passenger hard costs of delay per minute, by three cost scenarios

Delay (mins)	5	15	30	60	90	120	180	240	300
Low scenario	0.04	0.08	0.14	0.25	0.34	0.43	0.59	0.74	0.88
Base scenario	0.06	0.14	0.24	0.41	0.56	0.70	0.96	1.20	1.44
High scenario	0.07	0.17	0.29	0.50	0.68	0.85	1.17	1.47	1.75

Euros per minute, per passenger (2010).

Passenger soft costs

3.6.13 The passenger soft cost of delay is often a dominant component in the economics of airline unpunctuality ([31], [1]). Nevertheless, it remains poorly understood, with almost no quantitative costs published.

3.6.14 Soft costs can only be properly understood through market research. The relationship between airline unpunctuality and passenger tolerance, airline market share and corporate performance, has been discussed by several authors, such as: Bieger et al. [22], Dresner and Xu [23], Sauerwein et al. [24], Sultan and Simpson [25], Suzuki et al. [26] and Teichert et al. [27]. Oldfield [28] specifically demonstrates how United Airlines customer satisfaction scores are 'strongly correlated' with on-time performance. The treatment by Ball et al. [21] is discussed in Annex C.

3.6.15 European airline markets have become increasingly price driven, with many 'traditional' airlines no longer providing free catering on shorter hauls. Low-cost carriers (have continued to) enjoy a considerable share of the business-purpose market. Increased distribution through the internet has also helped to keep fares down and competition up. A discussion of UK complaints data on delays [14] also supports the view that there has been no recent marked increase in delay sensitivity, during a period of worsening actual delay experienced.

3.6.16 It is assumed [14] that the average (base scenario) value of the soft cost published in 2004 (EUR 0.18 per passenger minute of delay[1]) had not increased by 2008. This is in contrast to the airline hard costs of passenger delay, which generally have increased (see previous section on passenger hard costs, and summary statement in Section 3.6.21). As with the hard costs, a net compound inflationary increase for 2008 to 2010 of 1.81% is added (see Annex E).

3.6.17 For distributing the soft costs of delay, a logit function [14] is used to describe passenger dissatisfaction (δ; normalised) against various levels of delay. This curve is used to distribute the soft cost as a function of delay duration, and may be thought of as a proxy for the propensity of a passenger to switch from a given airline, to some other choice, after trips with given delay experiences.

$$\delta = \frac{1}{k(1+e^{a-bt^c})} - k'$$

3.6.18 This is plotted in Figure 8 (black curve) and has the desirable characteristics of maintaining a low value for some time, then rapidly increasing through a zone of 'intolerance', before levelling off. Quantification of the saturation of delay inconvenience[14] and crossovers in Kano [29] customer satisfaction 'requirements'[15] contributed towards the model. Relationships between market share, punctuality and customer satisfaction were also examined.

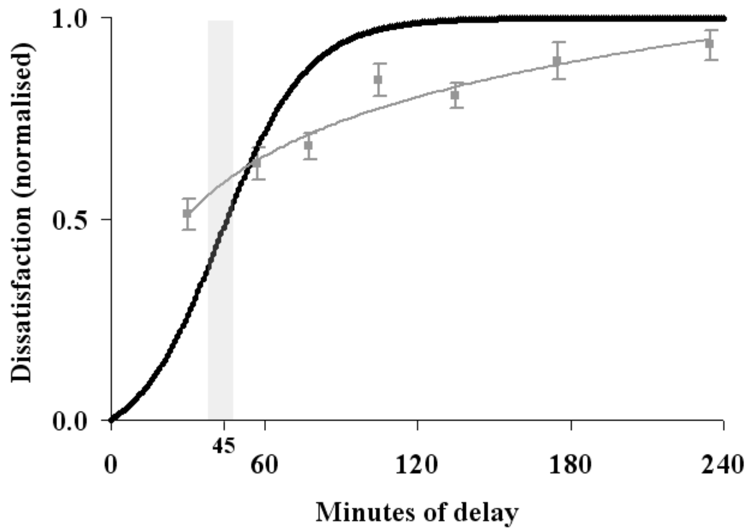

Figure 8. Passenger dissatisfaction as a function of delay duration

3.6.19 Euro costs are assigned using δ as a weight, such that when the costs of delay in each delay band of Table B4 (2007 values used for consistency) are multiplied by the relative proportion of delays in the band, the original aggregate value is obtained (EUR 0.183 per passenger, per minute of delay for the base case scenario). The cost ratio between scenario costs for each delay magnitude is linear (from [14]). The values below are quoted by the delay magnitudes introduced in Section 1.1.10.

Table 18. Passenger soft costs of delay per minute, by three cost scenarios

Delay (mins)	5	15	30	60	90	120	180	240	300
Low scenario	0.01	0.02	0.07	0.19	0.25	0.27	0.27	0.27	0.27
Base scenario	0.02	0.09	0.25	0.69	0.91	0.96	0.97	0.97	0.97
High scenario	0.03	0.10	0.28	0.77	1.01	1.06	1.08	1.08	1.08

Euros per minute, per passenger (2010).

[14] Grey curve: bespoke survey [14], leisure-purpose passengers.
[15] Shaded rectangle shows boundary of intolerance for business-purpose passengers: analysis based on literature data [30].

3.6.20 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). For the calculations of this report, 10% of the soft costs in Table 18 are used: this is a working estimate (limited evidence for the use of a small value is presented in [14]; the need for further work is highlighted in Section 5). The exception is in Annex D, where **single-flight trade-offs** are made, where the full soft costs in Table 18 are used.

Summary of 2010 passenger costs

3.6.21 Overall, the aggregate, *total* passenger base cost scenario for 2010 is 22% higher than the 2004 value previously reported [1] (with the full soft cost included, to compare like with like). 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. Future work required in this area is discussed in Section 5.

3.7 Reactionary costs

Introduction to reactionary costs

3.7.1 The tactical costs discussed in the previous sections need to be scaled up to the network level. 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). These need to be factored in to the tactical delay cost calculations.

3.7.2 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 airline's 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') aircraft (flight 'X') on subsequent legs (rotational reactionary effect, e.g. flight 'Y'), but also other aircraft (non-rotational reactionary effect, flights 'A', 'B', … etc).

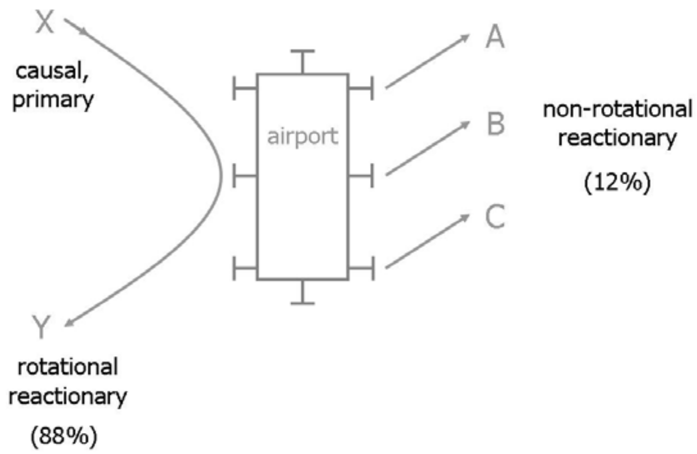

Figure 9. Reactionary delays

3.7.3 The 2009 European reactionary to primary delay ratio of approximately 0.8 (0.82 system level ratio of departure delay as reported by airlines to CODA; [10]) means that for each minute of primary delay, on average, another 0.8 minutes of reactionary delay are generated in the network. (The value was 0.85 in 2008 [10].) This is often expressed in the literature as a multiplier, e.g. 1.8.

3.7.4 For both 2008 and 2009, the ratio of rotational to non-rotational delay minutes was 88:12 [10] (Figure 9). This is at the system level; it can vary significantly by airline.

3.7.5 Rather than simply multiplying all delay costs by a common factor (e.g. 1.8) to obtain the total network cost (primary plus reactionary cost), Beatty et al. [15] studied delay propagation using American Airlines' schedule data, building delay trees, which included schedule buffers.

3.7.6 Based (in part) on the Beatty model, the multipliers we have developed (see Table 19) take into account the magnitude of the primary delay. When the basic multipliers for the ranges of delay in Table B4 are weighted by the proportion of delayed flights in each range, the weighted average is 1.8. The values below are quoted by the delay magnitudes introduced in Section 1.1.10.

Table 19. Basic reactionary multipliers by delay magnitude

Delay (mins)	5	15	30	60	90	120	180	240	300
Basic multiplier	1.49	1.67	1.94	2.47	3.01	3.54	4.61	5.67	6.74

3.7.7 In our models, all reactionary delay is treated as at-gate delay, either for onward flights from the same airport (flights 'Y'; 'A', 'B', … etc) or on subsequent rotations. Non-rotational reactionary delay is based on European 'average' aircraft (see Section 3.7.31 et seq).

3.7.8 As stated in [14], if used directly as they appear in the table above, these basic multipliers often overestimate the reactionary costs. Simply assigning, for example, one rotational delay of 60 minutes produces rather higher costs than two delays of 30 minutes – this is because passenger per-minute costs increase with length of delay.

3.7.9 Further modelling suggests that the basic model of Beatty et al. [15] needs to be adjusted in different ways for narrowbody and widebody rotational delays. Joint constraints are: over how many rotations the reactionary delay may be distributed; how much delay is assigned to each rotation; and, avoiding night curfews on the final rotation. Model refinements are discussed next, first for narrowbodies.

Refining the basic rotational model – narrowbodies

3.7.10 Narrowbodies typically have 5 rotations per day (see Table B1). If the first rotation has a primary delay of around 2 hours, this causes another 4 hours in total of rotational delay (as a good approximation[16]).

[16] Interpolation from the preceding table of basic reactionary multipliers actually predicts that 1hr53 of primary delay produces, on average, 4hr00 of *rotational* reactionary delay (using the 88:12 ratio cited in Section 3.7.4).

3.7.11 **Low cost scenario.** Four hours such as these could be 'accommodated' within a typical narrowbody operational day as one hour on each rotation after the primary delay, for example. Airlines may sometimes put more schedule buffer early in the day to absorb delay. This example reflects some initial recovery (primary delay of 2 hours; next rotational delay 1 hour) and no further recovery. In general, splitting the reactionary delay into four equal parts produces a relatively low cost estimate.

3.7.12 **High cost scenario.** Assigning a large, at-gate rotational delay (such as 4 hours) to just *one* of the subsequent rotations after the primary delay, means, by definition, that zero rotational delay is assigned to the other rotations. If such a single, large delay is all on an early rotation, attaining zero delay on later rotations may require very uncommon reductions in turnarounds. This is the limiting case adopted for the high cost scenario.

3.7.13 **Base cost scenario.** Likely distributions are diminishing ones over subsequent rotations, such as 60:30:10 or 50:30:20, or interim reductions such as 60:10:30. Some insightful studies have been produced (e.g. [34], [35]). It is difficult to accurately separate pure propagated delay from compounding effects, like missing ATFM slots on subsequent rotations. For simplicity in the base case scenario, a simple 50:50 split (equally over two rotations) is used, as a reasonable approximation[17].

3.7.14 **Capping.** Simple models suggest that total reactionary delay of much more than 4 hours are difficult to allocate to typical narrowbody operational days, without making a significant change, such as cancelling one or more rotations. Our model caps these costs at the cost of four hours of *total* rotational minutes under any given scenario. For a base case scenario B735 (113 seats, Table B2) this equals EUR 17 230. This compares to an approximate estimate in EUROCONTROL's 'Standard Inputs' [4] of the average cost of cancelling a 120-seat narrowbody flight, of EUR 16 000.

3.7.15 **Model assumptions.** We have here attempted to use reasonable assumptions, based on basic operational considerations, to generate a realistic set of reactionary scenarios for narrowbody rotational delay. Further operations-based research is required, preferably with tail-specific data covering several European airlines. The narrowbody assumptions are summarised in the table below. The figure summarises the outputs of the scenarios.

Table 20. Number of rotations over which narrowbody delay distributed

Reactionary delay (hours)	Low	Base	High
$0 < t \leq 4$	4	2	1
$4 < t$ (capped)	4 x 1 hour	2 x 2 hour	1 x 4 hour

[17] This simple split only yields cost differences of up to 25% for the passenger hard costs, compared with either a 60:30:10 or 50:30:20 split. The *total* percentage cost differences are less, since passenger hard costs are not the only component of the cost of delay.

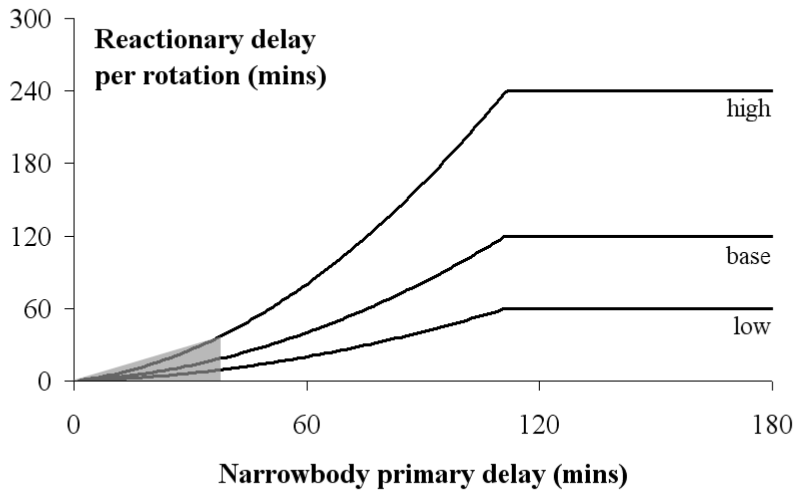

Figure 10. Narrowbody rotational reactionary delay

3.7.16 **Recovery.** The grey shaded triangle shows where the total rotational reactionary delay is less than the primary delay. For example, inside the triangle, 15 minutes of primary delay causes around 10 minutes of rotational reactionary delay. Outside the triangle, 60 minutes of primary delay produces just under 80 minutes of reactionary delay; where this is assigned equally over two rotations, for example in the base cost scenario, this implies 20 minutes' recovery on the first such rotation. Such recoveries are largely made through schedule buffer and slack-time at-gate, and sometimes by achieving a faster turnaround at the gate. The high scenario curve (all the delay is here assigned to one rotation) shows the total reactionary delay for any scenario.

Refining the basic rotational model - widebodies

3.7.17 Compared with the narrowbody case, it is less straightforward to generically model widebody rotations, not least due to the geographical scale and variability of such operations. For example, some eastbound flights may have quite long layovers in order that the westbound return rotation will land after a morning curfew (or at a more desirable time of day for passengers). Widebody aircraft are more likely to have overnight layovers than narrowbodies and to be able to make substantial airborne recoveries, e.g. due to favourable winds. Time zone differences may also lead to schedule bunching at certain times of the day.

3.7.18 Due to considerably longer flight times, widebodies have fewer rotations in an operational day (see Table B1) and there may be more opportunity to absorb delay on certain rotations (e.g. with particularly long layovers). This suggests spreading widebody reactionary delay over fewer rotations than the narrowbody case.

3.7.19 **Low cost scenario.** It is highly unlikely that widebody delay will persist over such a long timescale as four rotations (as used in the narrowbody low cost scenario). For the low cost widebody scenario, a 50:50 split is assumed over two reactionary rotations (typically spread over more than one operational day - see Table B1).

3.7.20 **High cost scenario.** For the high cost scenario, as with narrowbodies, the reactionary delay is assigned to one rotation.

3.7.21 **Base cost scenario.** A 'statistical' cost, split over 1.5 rotations, is assigned here (1.5 being the mid-point between the low and high cost scenarios). This is statistically equivalent to allocating 60 minutes of primary delay split separately as 45 and 15 minutes.

3.7.22 **Capping.** Compared to the narrowbody case, with fewer rotations over which to distribute delay but longer layovers in which to potentially reduce them, we have judgementally assigned a cost cap of five hours to the widebody case (in practice, such flights might be cancelled at longer or shorter delay). This refers to a limit of assigning five hours of *total* rotational minutes under any given scenario. For a base case scenario B744 (403 seats, Table B2) this equals EUR 106 400. This compares to an approximate estimate in EUROCONTROL's 'Standard Inputs' [4] of the average cost of cancelling a 400-seat widebody flight, of EUR 75 000.

3.7.23 **Model assumptions.** We have again attempted to use reasonable assumptions, based on basic operational considerations, to generate a realistic set of reactionary scenarios for widebody rotational delay. Further research is required on eastbound and westbound long-haul operations out of Europe to produce more refined models, with a more detailed consideration of operational decision making, particularly regarding widebodies out of position. The widebody assumptions are summarised in the table below. The figure summarises the outputs of the scenarios.

Table 21. Number of rotations over which widebody delay distributed

Reactionary delay (hours)	Low	Base	High
0 < t ≤ 5	2	'1.5'	1
5 < t (capped)	2 x 2.5 hours	4hr20 + 0hr40	1 x 5 hour

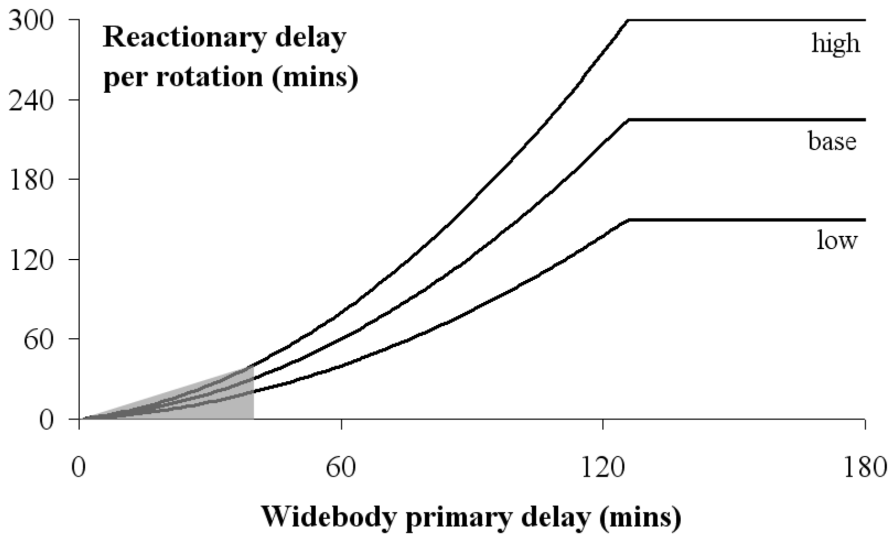

Figure 11. Widebody rotational reactionary delay

3.7.24 **Recovery.** As with the narrowbodies, the high scenario curve may be compared with the grey shaded triangle, which then represents the zone in which the total rotational reactionary delay is less than the primary delay. As with the narrowbodies, the high cost scenario curve is the steepest of the three. (The base curve is drawn for the larger of the two reactionary delays, calculated according to the split described above).

How the reactionary model treats different cost elements

3.7.25 The rotational reactionary model is applied in a tailored way for each of the costs discussed in the previous sections (fuel, maintenance, crew and passenger). As stated, all reactionary delay is assumed to occur at-gate. For fuel, the cost is therefore zero, since the at-gate model assumes that the APU and engines are off. The other costs are discussed in the following paragraphs. The narrowbody and widebody cost caps apply to all of these calculations.

3.7.26 The passenger costing is straightforward, since each new rotation is assumed to have new passengers on-board (a simplification discussed further in Section 5). This means that the reactionary minutes are multiplied by the corresponding hard and soft tactical costs derived in Section 3.6. The reader is reminded of the *caveat* of Section 3.6.20.

3.7.27 For the tactical maintenance costs: **(i)** where the rotational reactionary delay is less than the primary delay, no additional costs are added, nor are any cost savings calculated, as a result of the implied recovery; **(ii)** where the rotational reactionary delay is equal to the primary delay, no additional costs are added; **(iii)** where the rotational reactionary delay is greater than the primary delay, the cost associated with the additional reactionary delay is added once only[18].

3.7.28 For the tactical crew costs, care needs to be taken to avoid double-counting and to take account of crew changes. Crew are assumed to remain the same for two narrowbody rotations but to change on each widebody rotation. For narrowbody crew, rotations are costed as **paired rotations** - a combined calculation over both rotations is made for one set of crew. This applies to a primary rotation and a following reactionary rotation and/or to subsequent, sequential reactionary rotations.

3.7.29 On **crew change** (narrowbodies and widebodies) with a delayed flight, whether a cost is incurred depends on whether the new crew were advised to start their shift later (or a crew swap was carried out). High cost scenarios are fully costed (as per Table 16). For base scenarios, half the cost per minute (Table 16) is used. (For all low cost scenarios, crew are costed at zero).

3.7.30 For narrowbody crew only, within a paired rotation (no crew change) if the delay on the second rotation is less than the one before it, the cost difference is recovered. In such cases, this means that a reactionary cost correction is subtracted from the primary cost[19] (except for an 'apparent' recovery solely arising as the result of a cap). Otherwise, for two sequential reactionary rotations with delay, the cost is only considered once (and set to zero in the low cost scenario).

Non-rotational model - all aircraft

3.7.31 The non-rotational reactionary costs are more straightforward to allocate. It has already been stated that these represent 12% of all reactionary delays. Using 12% with the basic multipliers (see Table 19) gives a simple estimate of the number of non-rotational reactionary minutes for each primary delay.

3.7.32 It is assumed that these are all experienced by secondary aircraft waiting at-gate (flights 'A', 'B', … etc, Figure 9) for the causal aircraft (flight 'X'). No modelling of passenger or crew dependencies between the secondary and causal aircraft is included (see Section 5). Each non-rotational reactionary delay is thus treated as a new at-gate delay.

[18] Even on subsequent rotations with respect to schedule this still relates to the same aircraft and must not be double-counted.
[19] This means that at very low delay for narrowbodies (only for 5 minutes of primary delay for jets, up to 15 minutes for ATRs), the *total* delay cost may be less than the primary delay (by up to EUR 10 for base scenario, up to EUR 40 for high scenario).

3.7.33 In terms of estimating typical aircraft connectivities in Europe, various approaches are possible. Analysing actual booking data from Global Distribution Systems would be time consuming and prohibitively expensive, although this would give a very good estimate. Another method would be to examine permutations of origin and destination via all possible airports with agreed Minimum Connection Times, using OAG data. This would be a very large computational task, however[20].

3.7.34 A simpler approach is to use the total number of flights for each of the twelve supported aircraft (see Table B3) and to normalise these to produce a distribution which totals 100%. These flight frequencies cannot be guaranteed as a representative estimate of connection frequencies but this seems to be a reasonable approach. These aircraft represent over 50% of all IFR flights in 2009 (Table B3).

3.7.35 For each primary delay, the non-rotational reactionary minutes (primary delay x [1 - basic multiplier] x 12%) are converted to an at-gate cost for each of the twelve supported aircraft and then proportioned over the normalised distribution of these aircraft to give the weighted average.

3.7.36 In the absence of superior data, the passenger costs are assigned (by judgement) to eight rotations, which could be considered as being spread over two rotations for each of four connecting aircraft. Whilst no specific cap is applied, this spreading of the cost reduces what would otherwise be an unrealistically high assignment of the passenger costs as single lots.

3.7.37 For the crew and maintenance costs, this cost spreading is not an issue, since the per-minute cost is not a function of the magnitude of the delay. These costs are assigned as a simple ratio (12%/88%) of the corresponding rotational reactionary cost. Where this corresponds to a negative crew cost (the correction applied at some lower delays for crew - see Section 3.7.30), zero cost is assigned.

Using the reactionary costs

3.7.38 Section 3.8.2 presents the full tactical costs (i.e. including both the rotational and non-rotational reactionary costs described in this section) for each phase of flight, summing the primary and reactionary maintenance, crew and passenger costs per minute. The off-gate costs (taxi, cruise extension and arrival management) in Section 3.8.2 also include the cost of fuel.

3.7.39 Reactionary cost calculations will be developed further in future years in our on-going research programme – it is recognised as being a highly complex domain. However, every effort has been made to adopt a methodology that is as robust as possible and least likely to be (radically) affected by future refinements. Such a contingency is also partly covered by the range of values presented, from the 'low' through to the 'high' cost scenarios. See Section 5 for further discussion of future possible work.

[20] The case of Heathrow to Schiphol, then onward to any point in Europe, with a three hour Minimum Connection Time at Schiphol, alone generates over 4000 possibilities (OAG (2008), personal communication). It would then be non-trivial to identify the likelihoods of actual connections made.

3.8 Tabulations of tactical costs

3.8.1 This section presents the base scenario primary tactical costs (i.e. excluding the reactionary costs) for each phase of flight, summing the maintenance, crew and passenger costs per minute, derived in sections 3.3 - 3.6. The off-gate costs (taxi, en-route and arrival management) also include the cost of fuel (Section 3.2). The low and high cost scenario tables are to be found in Annex G, to avoid presenting a very cluttered section here. Section 4 discusses the use of these costs.

Table 22. AT-GATE / BASE / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	70	340	1 010	3 250	6 350	10 140	19 700	31 820	46 350
B734	80	370	1 110	3 630	7 150	11 440	22 330	36 140	52 710
B735	70	310	920	2 930	5 720	9 120	17 700	28 570	41 590
B738	80	410	1 230	4 010	7 910	12 670	24 740	40 060	58 440
B752	90	470	1 460	4 850	9 620	15 460	30 290	49 150	71 810
B763	130	690	2 150	7 170	14 240	22 900	44 920	72 920	106 570
B744	190	970	3 050	10 240	20 400	32 850	64 520	104 840	153 310
A319	70	340	1 020	3 320	6 540	10 480	20 450	33 110	48 300
A320	80	380	1 150	3 770	7 460	11 960	23 390	37 900	55 330
A321	80	430	1 350	4 490	8 920	14 360	28 170	45 730	66 850
AT43	40	160	430	1 260	2 390	3 750	7 140	11 400	16 460
AT72	50	190	540	1 660	3 200	5 060	9 720	15 580	22 590

Euros, total (2010). Without reactionary costs.

Table 23. TAXI / BASE / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	130	500	1 320	3 870	7 290	11 380	21 580	34 320	49 470
B734	130	540	1 450	4 310	8 170	12 800	24 360	38 850	56 100
B735	120	480	1 250	3 590	6 710	10 440	19 690	31 210	44 900
B738	130	550	1 530	4 610	8 810	13 870	26 530	42 440	61 420
B752	170	710	1 930	5 790	11 040	17 350	33 120	52 930	76 530
B763	230	970	2 720	8 300	15 940	25 160	48 310	77 440	112 220
B744	350	1 470	4 060	12 250	23 410	36 870	70 550	112 880	163 360
A319	120	480	1 300	3 880	7 380	11 590	22 120	35 340	51 090
A320	130	550	1 490	4 460	8 490	13 340	25 450	40 660	58 770
A321	140	590	1 670	5 140	9 900	15 660	30 120	48 340	70 100
AT43	60	220	550	1 520	2 780	4 270	7 910	12 420	17 740
AT72	70	270	700	1 970	3 660	5 670	10 630	16 800	24 120

Euros, total (2010). Without reactionary costs.

Table 24. EN-ROUTE / BASE / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	210	750	1 830	4 890	8 810	13 420	24 630	38 390	54 560
B734	210	780	1 930	5 270	9 610	14 720	27 250	42 700	60 910
B735	190	690	1 670	4 430	7 970	12 120	22 210	34 580	49 100
B738	220	830	2 080	5 710	10 450	16 060	29 820	46 830	66 900
B752	280	1 020	2 560	7 060	12 930	19 870	36 900	57 970	82 830
B763	390	1 470	3 710	10 290	18 920	29 140	54 270	85 390	122 160
B744	710	2 540	6 190	16 530	29 820	45 410	83 360	129 960	184 720
A319	200	730	1 810	4 900	8 910	13 630	25 180	39 410	56 180
A320	210	770	1 940	5 370	9 850	15 150	28 170	44 280	63 300
A321	240	900	2 290	6 380	11 760	18 130	33 830	53 280	76 280
AT43	70	240	600	1 610	2 910	4 440	8 170	12 770	18 170
AT72	90	310	790	2 150	3 930	6 020	11 170	17 520	25 010

Euros, total (2010). Without reactionary costs.

Table 25. ARRIVAL MGT / BASE / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	180	670	1 660	4 550	8 310	12 740	23 610	37 040	52 870
B734	200	750	1 880	5 160	9 450	14 510	26 920	42 270	60 370
B735	160	580	1 460	4 020	7 350	11 290	20 960	32 920	47 030
B738	210	780	1 980	5 520	10 170	15 680	29 250	46 070	65 950
B752	240	910	2 330	6 590	12 230	18 940	35 510	56 110	80 510
B763	370	1 410	3 580	10 030	18 530	28 620	53 490	84 350	120 860
B744	540	2 030	5 170	14 490	26 760	41 330	77 250	121 810	174 530
A319	190	690	1 720	4 730	8 660	13 300	24 680	38 750	55 360
A320	210	770	1 930	5 330	9 800	15 080	28 070	44 150	63 140
A321	230	860	2 200	6 200	11 490	17 770	33 290	52 560	75 380
AT43	70	240	600	1 600	2 900	4 430	8 160	12 750	18 160
AT72	80	300	750	2 090	3 830	5 900	10 980	17 270	24 700

Euros, total (2010). Without reactionary costs.

3.8.2 This section presents the base scenario **full** tactical costs (i.e. including both the rotational and non-rotational reactionary costs described in Section 3.7) for each phase of flight, summing the (primary and reactionary) maintenance, crew and passenger costs per minute, derived in sections 3.3 - 3.6. The off-gate costs (taxi, en-route and arrival management) also include the cost of fuel (Section 3.2). The low and high cost scenario tables are to be found in Annex H, to avoid presenting a very cluttered section here. Section 4 discusses the use of these costs.

Table 26. AT-GATE / BASE / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	60	360	1 290	5 780	15 710	29 730	39 990	53 720	71 300
B734	70	400	1 430	6 510	17 820	33 670	45 260	60 680	80 310
B735	60	330	1 170	5 200	14 120	26 740	36 020	48 490	64 570
B738	70	440	1 580	7 200	19 730	37 270	50 050	66 970	88 410
B752	80	520	1 900	8 780	24 170	45 610	61 150	81 610	107 330
B763	150	880	3 130	14 510	39 380	84 200	119 910	149 510	186 220
B744	220	1 230	4 440	20 760	56 480	120 940	172 030	213 950	265 480
A319	60	370	1 310	5 960	16 330	30 880	41 560	55 820	74 070
A320	70	410	1 490	6 800	18 680	35 280	47 420	63 530	84 020
A321	70	470	1 770	8 150	22 490	42 460	56 980	76 140	100 320
AT43	30	160	520	2 160	5 730	10 940	15 040	20 900	29 020
AT72	40	190	670	2 900	7 780	14 800	20 160	27 630	37 690

Euros, total (2010). With reactionary costs.

Table 27. TAXI / BASE / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	120	520	1 600	6 400	16 650	30 970	41 870	56 220	74 420
B734	120	570	1 770	7 190	18 840	35 030	47 290	63 390	83 700
B735	110	500	1 500	5 860	15 110	28 060	38 010	51 130	67 880
B738	120	580	1 880	7 800	20 630	38 470	51 840	69 350	91 390
B752	160	760	2 370	9 720	25 590	47 500	63 980	85 390	112 050
B763	250	1 160	3 700	15 640	41 080	86 460	123 300	154 030	191 870
B744	380	1 730	5 450	22 770	59 490	124 960	178 060	221 990	275 530
A319	110	510	1 590	6 520	17 170	31 990	43 230	58 050	76 860
A320	120	580	1 830	7 490	19 710	36 660	49 480	66 290	87 460
A321	130	630	2 090	8 800	23 470	43 760	58 930	78 750	103 570
AT43	50	220	640	2 420	6 120	11 460	15 810	21 920	30 300
AT72	60	270	830	3 210	8 240	15 410	21 070	28 850	39 220

Euros, total (2010). With reactionary costs.

Table 28. EN-ROUTE / BASE / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	200	770	2 110	7 420	18 170	33 010	44 920	60 290	79 510
B734	200	810	2 250	8 150	20 280	36 950	50 180	67 240	88 510
B735	180	710	1 920	6 700	16 370	29 740	40 530	54 500	72 080
B738	210	860	2 430	8 900	22 270	40 660	55 130	73 740	96 870
B752	270	1 070	3 000	10 990	27 480	50 020	67 760	90 430	118 350
B763	410	1 660	4 690	17 630	44 060	90 440	129 260	161 980	201 810
B744	740	2 800	7 580	27 050	65 900	133 500	190 870	239 070	296 890
A319	190	760	2 100	7 540	18 700	34 030	46 290	62 120	81 950
A320	200	800	2 280	8 400	21 070	38 470	52 200	69 910	91 990
A321	230	940	2 710	10 040	25 330	46 230	62 640	83 690	109 750
AT43	60	240	690	2 510	6 250	11 630	16 070	22 270	30 730
AT72	80	310	920	3 390	8 510	15 760	21 610	29 570	40 110

Euros, total (2010). With reactionary costs.

Table 29. ARRIVAL MGT / BASE / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	170	690	1 940	7 080	17 670	32 330	43 900	58 940	77 820
B734	190	780	2 200	8 040	20 120	36 740	49 850	66 810	87 970
B735	150	600	1 710	6 290	15 750	28 910	39 280	52 840	70 010
B738	200	810	2 330	8 710	21 990	40 280	54 560	72 980	95 920
B752	230	960	2 770	10 520	26 780	49 090	66 370	88 570	116 030
B763	390	1 600	4 560	17 370	43 670	89 920	128 480	160 940	200 510
B744	570	2 290	6 560	25 010	62 840	129 420	184 760	230 920	286 700
A319	180	720	2 010	7 370	18 450	33 700	45 790	61 460	81 130
A320	200	800	2 270	8 360	21 020	38 400	52 100	69 780	91 830
A321	220	900	2 620	9 860	25 060	45 870	62 100	82 970	108 850
AT43	60	240	690	2 500	6 240	11 620	16 060	22 250	30 720
AT72	70	300	880	3 330	8 410	15 640	21 420	29 320	39 800

Euros, total (2010). With reactionary costs.

4 Illustrated examples and guidelines on using the costs

4.1.1 **Use of averages.** This section discusses the way in which the costs derived in this report may be used, for example in the context of performance assessment and cost-benefit analysis. Where average values are quoted, it is strongly recommended that these are used as indicators and/or insights into delay costs, rather than for specific analyses or operational planning. Numerous tables have been presented elsewhere in the report offering more detailed cost breakdowns.

4.1.2 **Cost-base.** The costs derived in this report are newly derived in 2010 Euros[21].

4.1.3 **Tactical delay costs.** These are incurred on the day of operations. In most cases, it is anticipated that the user will find it appropriate to use the full tactical costs, presented in tables 26 - 29, for calculating these costs of delay. These include the reactionary costs of 'knock-on' delay in the rest of the network, which it is usually pertinent to include. Examples are given below.

4.1.4 **Strategic delay costs**. These are costs accounted for advance. Strategic costs will typically be used for assessing the cost of adding buffer to schedule. This could be by airline choice, or forced by scheduling constraints at an airport (and thus be considered as a cost of congestion, albeit one which off-sets tactical delay costs). Strategic costs may also be incurred as a consequence of factors that contribute to an increase in flight time in a predictable way, such as delay due to route design. Examples are given below.

4.1.5 **Long delays.** Care should be exercised when using cost of delay values for long delays in certain phases of flight. For consistency, most of the tables and figures show delays of up to 300 minutes, although such long delays are not feasible in all contexts (e.g. arrival management).

4.1.6 **Compound tactical delays.** When calculating the cost of tactical delays, many of these will have more than one contributing factor. For example, a 5 minute arrival management delay may well be incurred in addition to an existing departure delay, e.g. of 10 minutes. Due to the tactical cost non-linearities, the total cost of the 15 minute delay is not simply the sum of the 10 and 5 minute delays - it will (usually) be higher. In the absence of appropriate data, assumptions may need to be made when estimating such costs.

4.1.7 **ATFM costs.** Table 30 presents the high-level ATFM costs that are derived in detail in Annex J. The total European cost of ATFM delay (for all causes and including reactionary costs) is estimated as **EUR 1 250 million**. As remarked upon in the Executive Summary, 92% of flights (in 2009; see footnote 21) had no ATFM delay. 748 830 flights had some ATFM delay. The average cost of delay of an ATFM delayed flight is **EUR 1 660**. (Note. The total ATFM delay cost averaged over *all* flights is approximately EUR 130: EUR 1 660 x 8%.) Dividing the total cost by the total number of ATFM minutes (15.3 million) gives a value of **EUR 81**. (As detailed in Annex J, these cost calculations use delay-weighted values. Costs are quoted to three significant figures.)

[21] Some high-level costs have been derived using 2009 traffic data [10] as weights (since 2010 traffic data were not available at the time of press).

Table 30. European ATFM delay cost estimates

Factor	Cost
Network total cost of ATFM delay (all causes)	**1 250 million**
Average cost of delay of an ATFM delayed aircraft	**1 660**
Network average cost of ATFM delay, per minute	**81**

Costs in 2010 Euros. Delay weights use 2009 ATFM data.

4.1.8 **Use of ATFM costs.** The value cited in Table 30 of EUR 81 per minute is a high-level average. It should be used with some caution in an operational context: different values may be obtained for other airspace areas (with different aircraft and delay distributions). As noted, delays experienced by aircraft are often compound. These high-level ATFM calculations make the approximation that they are independent.

4.1.9 **Cost factors.** The cost factor methodology of this report allows any given delay cost calculated to be presented by its individual components, as shown in Figure 12 (base cost scenarios are used; see tables 26 and 28 for (other) aircraft totals). Passenger costs dominate at-gate delays (and hence reactionary costs), whilst fuel costs form a significant proportion of en-route delay costs at lower delay.

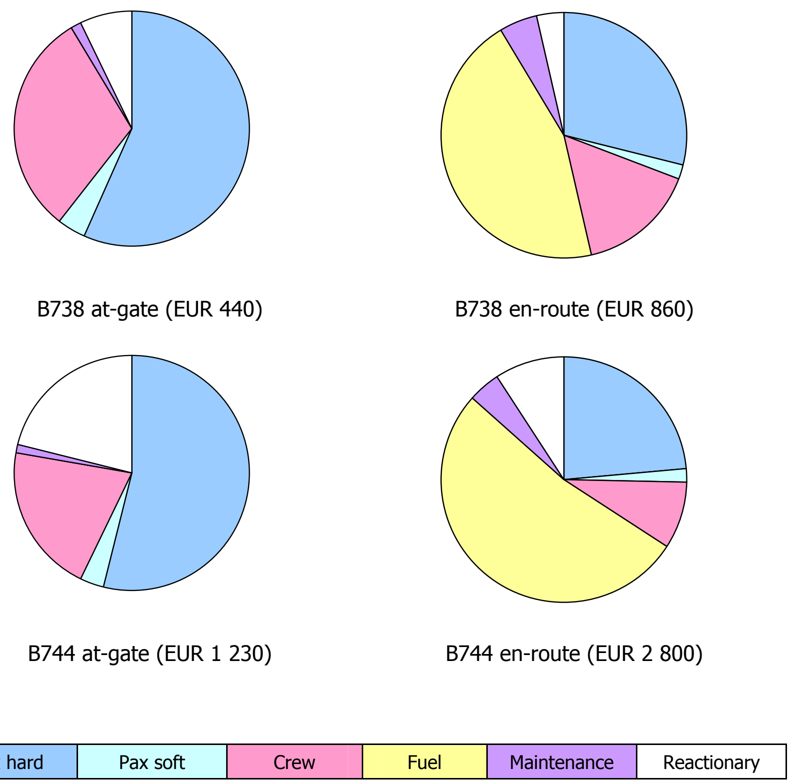

Figure 12. Example cost distributions for 15 min delays for B738 and B744

4.1.10 **Re-route trade-offs.** The calculation of a single-flight trade-off, i.e. costs for one tactical decision, is discussed in **Annex D**, where additional data tables and a simplified worked example are provided. No specific account is made of accelerated fuel burn (variable Cost Index settings) to recover the delay, however. This is an important consideration for future research (see also Section 5).

4.1.11 **En-route extension (tactical).** Fuel costs form a significant proportion of en-route delay costs at lower delay. Figure 13 shows how the fuel cost becomes proportionally less for en-route delay as the length of delay increases. At higher delay, it levels off at 8% (B738) and 10% (B744). At 120 minutes, the en-route costs are dominated by the passenger costs (from 80-90% across all aircraft types). These are tactical costs, as differentiated from route design costs (see Section 4.1.12).

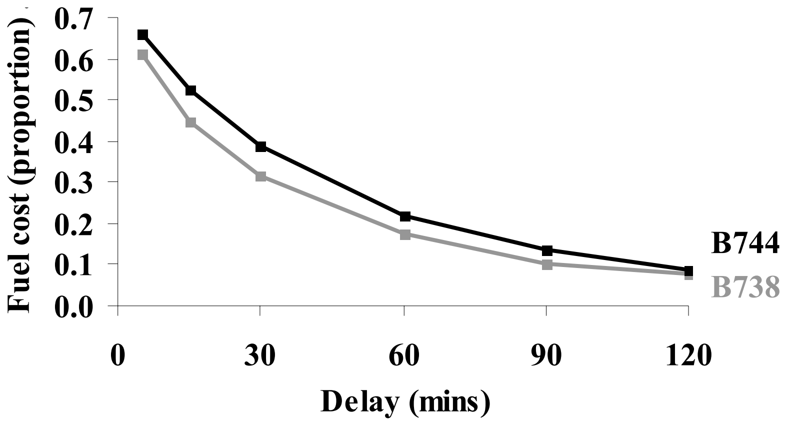

Figure 13. Proportional fuel cost as a function of delay duration

4.1.12 **En-route extension (strategic).** The costs presented in this report are scalable and thus may be multiplied over a period of time or a network (c.f. single-flight tactical trade-offs, discussed in Annex D). For en-route extension due to route design, for example, these are likely to be heavily dominated by strategic costs. For some cost calculations covering a period of time or network, it may be appropriate to use a combination of tactical and strategic costs. (For shorter delays, these costs might be quite similar. For en-route delay, each aircraft has some point in the 5-15 minutes range, where its strategic and tactical costs are equal).

4.1.13 **MTOW.** It has been demonstrated that MTOW (particularly √MTOW for full tactical costs) offers, in theory and empirically, good linear fits for cost. This allows the calculations to be extended to other aircraft, beyond the core set of twelve, to produce European high-level values. (See also **Annex J**.)

4.1.14 **Schedule buffer trade-offs.** A key use of the strategic costs of delay is the estimation of the cost-benefit of adding buffer to schedule. Simplified examples of such calculations are detailed in **Annex I**. These use the strategic costs of Table 9 and the primary costs of Table 22.

4.1.15 **Emissions charges.** Emissions costs are not considered. These will have an impact on future delay costs, by effectively increasing the cost of fuel burn.

5 Opportunities for future research and cost updates

This Section outlines some of the key opportunities identified for future research. It is a selective, rather than exhaustive, list.

Reactionary delay and cancellation costs

5.1.1 We have attempted to use reasonable assumptions, based on basic operational considerations, to generate a realistic set of reactionary cost scenarios. Reactionary cost calculations will be developed further in future years in our on-going research programme. Every effort has been made in this report to adopt a methodology that is as robust as possible and least likely to be (radically) affected by future refinements. Such a contingency is also partly covered by the range of values presented, from the 'low' through to the 'high' cost scenarios.

5.1.2 Further operations-based research is required, preferably with tail-specific data covering several European airlines. This should examine: the variation of reactionary delay as a function of the time of day at which the primary delay occurs; en-route recovery (see 'Accelerated fuel burn', below); the relationships with passenger-centric metrics (e.g. passengers onboard inbound delayed aircraft may be transferring onto other flights affected by the inbound delay or they could even be on the next rotation of the delayed aircraft itself); and cancellation costs. As a lower priority, effects such as in-bound crew delaying subsequent flights might also be studied.

5.1.3 ATFM-specific effects in reactionary delay may also be considered, such as missing (a) subsequent ATFM slot(s) as a result of previous delay. There is an opportunity for tracking such (cost) effects through the operational day for specific aircraft and assessing the potential to improve the coordination with flow management processes. This would build on previous work in this area [42] and calculations such as those in Annex D, and could explore ways in which the different priorities of individual airlines may be reconciled with the benefit accrued at the network level.

5.1.4 The cost of cancellations is a related but distinct research area. Whilst these costs have not been addressed in this report, they have been compared with capped reactionary costs. Cancellations may cause step-increases in delay costs and themselves have associated reactionary costs. Ball et al. [21] estimate that (US) delay costs are 65% due to delayed flights (where 'delayed' refers to more than 15 minutes) and missed connections, 35% due to (late) cancellations.

Passenger costs and metrics

5.1.5 In Section 3.6.8, it was remarked upon that 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. Although the passenger is at the centre of ATM delivery, flight delays are still the only commonly-reported type of metric in both the US and Europe.

5.1.6 There is significant potential to explore and further develop the limited existing literature on passenger-centric delay metrics, as a future complement to measuring flight delay, and to build on the passenger 'hard' and 'soft' cost models summarised in this report. The latter would be best achieved through airline surveys for hard costs and passenger surveys (using conjoint analysis) for soft costs.

Broader delay metrics

5.1.7 Complementing passenger-centric metrics, there is also an opportunity to develop other KPIs relating to service delivery, building on measures of average delay and total delay. These should link the performance and economics of ATM by exploring, for example, **delay variance** (predictability) and **delay propagation** metrics and their relationship to **delay cost** (including the cost of emissions)**.**

5.1.8 Such research could further examine policy and operational implications emerging from the economics of punctuality target-setting. It cannot be economic best practice to arbitrarily set punctuality targets, such as "99% of flights within 5 minutes of schedule". Such targets need to be established within the context of proper cost-benefit analyses. For example, what is the alternative bottom-line impact of instead targeting 98 per cent of flights within 10 minutes of schedule?

Accelerated fuel burn

5.1.9 The calculation of a single-flight re-route trade-off, i.e. costs for one tactical decision, is discussed in Annex D. No specific account is made of accelerated fuel burn, however, whereby an aircraft may depart late and then attempt to recover all or part of the delay by flying faster than originally planned (using a higher Cost Index in the FMS). This may be considered to be *partially* addressed by proxy in the high cost scenarios, where the cost of fuel is higher, although a proper treatment of this issue is required. Use of higher Cost Index settings also has implications for maintenance costs (some contracts may penalise this) and, more importantly, for the predictability of aircraft trajectories, for example from the air traffic controller's perspective. Cost effects of accelerated fuel burn will be amplified when emissions charges are applied in the future.

4D trajectories

5.1.10 The SESAR ConOps is centred around the paradigm of trajectory-based operations, which aims to ensure that the airline flies a trajectory as close as possible to its intent and which is cost efficient (also balancing environmental constraints and respecting infrastructural constraints). With regard to the development of the 'Business Trajectory' an improved process is envisaged for obtaining the best 4D (e.g. taking into account the arrival time) trajectory. The User-Driven Prioritisation Process is a CDM negotiation process for managing the airlines' tactical priorities when there is a lack of capacity. The delay costs derived in this report, integrated with the future research opportunities identified in this section, will support newly quantifiable relationships between the performance and cost of a trajectory.

Future cost updates

5.1.11 Planned future work will fit simplified, yet robust, total delay cost curves for different phases of flight. It is anticipated that these will employ the √MTOW method of Annex J to extend the model to other aircraft types and will enable users to estimate delay costs based on a number of simple, available, input parameters. It would also be desirable if these new models included a simplified way of updating the costs in future (at least to a reasonable approximation) based on the methodologies of this report and with some degree of user-defined input.

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Annexes

Annex A
Glossary

ACARS	Aircraft Communications, Addressing and Reporting System
APU	Auxiliary Power Unit
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
BADA	Base of Aircraft DAta
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
CODA	Central Office for Delay Analysis (EUROCONTROL)
CRCO	Central Route Charges Office (EUROCONTROL)
CSA	CSA Czech Airlines (České aerolinie)
CTOT	Calculated Take-Off Time
ETOT	Estimated Take-Off Time
FAA	Federal Aviation Administration (United States)
FMS	Flight Management System
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
KLM	KLM Royal Dutch Airlines (Koninklijke Luchtvaart Maatschappij)
LTO	Landing/take-off cycle
MTOW	Maximum Take-Off Weight
MUICP	Monetary Union Index of Consumer Prices
OAG	Official Airline Guide
SEM	Standard error of the mean
SESAR	Single European Sky ATM Research (programme)
TMA	Terminal Manoeuvring Area (or Terminal Control Area)

Annex B
Technical data reference tables

Table B1. Aircraft designators, rotations, durations by phase, block hours

ICAO aircraft designation code	Aircraft	Rotations per day	Flight duration (mins)	Taxi hours per day	Turnaround at-gate (mins)	Block hours per day
B733	B737-300	4.5	90	1.4	80	8.2
B734	B737-400	4.1	100	1.5	90	8.2
B735	B737-500	5.1	80	1.5	70	8.2
B738	B737-800	4.0	120	1.3	70	9.3
B752	B757-200	2.7	200	0.9	90	9.8
B763	B767-300ER	1.8	390	0.8	120	12.3
B744	B747-400	1.5	510	0.7	180	13.9
A319	A319	4.9	90	1.5	60	8.8
A320	A320	4.4	110	1.6	60	9.7
A321	A321	4.2	120	1.5	60	9.8
AT43	ATR42-300	4.7	60	1.3	100	6.0
AT72	ATR72-200	5.0	60	1.2	90	6.3

All data values are averages
Main sources: ICAO [7] and EUROCONTROL [10]

Rotations (revenue landings / flights) per day (to 1 dp) from tail-number tracked (2009 [10]) data for widebodies; averaged with aircraft-weighted data (2008 [7]) for narrowbodies. Average flight durations (wheels off) sourced from ACARS (B752, B763, AT72; 2009 [10]) and CFMU (remaining aircraft; 2009 [10]) data (very similar values across data sets, preferred set chosen for fine-tuning of model). Average taxi hours (to 1 dp) derived from known [10] ratio to flight durations. Average at-gate turnaround (nearest 10 mins) refers to active *and passive/slack* time between rotations (see Section 1.1.3): for narrowbodies - derived from average number of rotations and flight durations with a 14-hour operational day; for widebodies, sourced from [1]. Average block hours per day (to 1dp) derived from previous four columns; validation: all agree to within 8% with calculations on data from [7] (outliers removed; weighted by number of aircraft; European aircraft only, except for A319 and B738 where two European low-cost carriers strongly dominated data available for 2008, therefore augmented with US and Canadian data).

Table B2. Aircraft seats and passenger loadings by scenario, plus MTOWs

ICAO aircraft designation code	Seats - low	Seats - base	Seats - high	Pax - low	Pax - base	Pax - high	MTOW (tonnes)
B733	149	127	127	89	95	114	60.4
B734	170	145	145	102	109	131	65.6
B735	133	113	113	80	85	102	55.2
B738	189	161	161	113	121	145	72.6
B752	235	200	200	141	150	180	107.1
B763	328	279	246	197	223	221	180.7
B744	474	403	356	284	322	320	392.5
A319	156	133	133	94	100	120	66.6
A320	180	153	153	108	115	138	73.6
A321	220	187	187	132	140	168	86.4
AT43	50	43	43	30	32	39	16.8
AT72	70	60	60	42	45	54	22.1

Seats and passenger numbers sourced from [5]. For load factors - see Section 3.6.6. MTOW values are derived from CRCO data for flights in 2008 and 2009, kindly supplied by PRU. Each MTOW is an average value across all flights, such that for a given aircraft type an MTOW value occurring twice as often as some other value, will have twice the relative weighting (i.e. one record per flight is used, with values that may vary by operator, equipment, powerplants, etc.).

Table B3. Flight numbers, durations and delays by aircraft type (2009)

Aircraft	Total[a] flights (number)	Total[a] flight duration (hours)	CFMU ATFM delays (hours)	ACARS[b] all delays (hours)
B733	354 285	532 623	11 392	32 630
B734	195 704	332 676	6 455	28 124
B735	205 375	287 970	6 618	16 788
B738	1 003 178	1 929 271	34 045	129 477
B752	172 734	622 318	5 988	23 689
B763	138 936	947 586	2 401	21 039
B744	144 208	1 222 028	1 938	24 666
A319	874 409	1 341 927	26 198	114 953
A320	1 148 476	2 011 756	42 839	142 738
A321	401 799	794 656	19 788	70 772
AT43	66 616	64 763	809	4 472
AT72	262 731	218 134	4 000	12 995
Total (all aircraft)	9 537 964	19 955 978	255 241	946 322

Key: *ACARS delays: Actual off-block* vs. *scheduled off-block, reported by airlines to CODA*
CFMU ATFM delays: CTOT vs. *ETOT*
[a] *IFR flights (CFMU)*
[b] *ACARS data for December 2009 below usual coverage at time of press*

Source: *[10]*

Table B4. Proportion of flights by delay ranges

Delay range (minutes)	1 -15	16 -30	31 -45	46 -60	61 -75	76 -90	91 -119	120 -179	180 -239	240 -299	300+
All flights (2007)	0.608	0.194	0.084	0.040	0.019	0.011	0.005	0.011	0.010	0.005	0.014

Delay range (minutes)	1 -4	5 -14	15 -29	30 -59	60 -89	90 -119	120 -179	180 -239	240 -299	300+
CFMU ATFM delays (2009)	0.045	0.420	0.348	0.152	0.024	0.007	0.004	0.001	0.000	0.000
ACARS all delays (2009[a])	0.232	0.367	0.211	0.119	0.035	0.015	0.012	0.004	0.002	0.003
Average difference (2009-2007)	-0.076		0.086	0.011	-0.001	0.006	-0.003	-0.007	-0.004	-0.012

Key: *ACARS delays: Actual off-block* vs. *scheduled off-block, reported by airlines to CODA*
CFMU ATFM delays: CTOT vs. *ETOT*
[a] *ACARS data for December 2009 below usual coverage at time of press*

Sources: 2007 data cited in [11], estimated from [12] and [13]
2009 data [10]

The weighting of the passenger costs in Section 3.6 uses the 2007 values in Table B4 to maintain consistency with previous publications (e.g. [11] and [14]). For the reactionary cost calculations of Section 3.7, the ACARS 'all delays' (2009) data have been used to produce up-to-date values, which includes a lower range (1-4 minutes) to improve differentiation at lower delay values. The bottom row of Table B4 shows that the 2009 - 2007 differences, partly attributable to differences in the range boundaries (especially where 15 minutes falls), are not very large.

Annex C
Passenger costs and 'value of time'

As reiterated at the outset of Section 3.6, this report specifically addresses delay costs to the *airline*, not wider costs of delay. It does not include passenger 'value of time', but does include the 'hard' and 'soft' costs of passenger delay to the airline.

'Value of time' is a concept widely used in cost-benefit analyses, particularly in transport economics. It is an opportunity cost, which corresponds to the monetary value associated with a traveller (passenger) during a journey. It is, essentially, how much a traveller would be willing to pay in order to save time during a journey (for example by travelling on a quicker service or a faster mode), or how much 'compensation' they would accept, directly or indirectly, for 'lost' time. A large body of research is dedicated to this highly complex area. A recent review and meta-analysis [41] considers 226 studies in the UK alone, which have produced 1749 valuations. Several key sources for air transport are summarised in EUROCONTROL's 'Standard Inputs' [4].

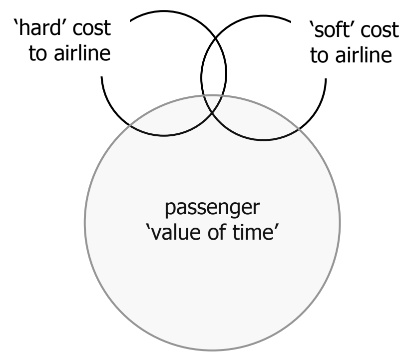

Figure C1. Approximate 'single-flight' costs of passenger delay

The relationship between the passenger hard cost, soft cost, and value of time is simplified in the figure above. These values may be mutually dependent in a complex way. If an airline pays more compensation to a delayed passenger (a hard cost), the passenger may be less likely to defect to another airline (thus reducing the associated soft cost) and may make an adjustment to their in-trip or post-trip value of time. However, to the maximum extent possible, we seek to differentiate these costs, which is at least reasonably practical as a first approximation, following the definitions of the hard and soft costs presented in Section 3.6: these two costs combined should cover every aspect of delayed passenger costs that impact the airline.

As explained in Section 3.6.20, 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: a passenger who has transferred their custom. When soft costs are considered in an **scalable** context (i.e. multiplied over a period of time or a network), only a certain amount of net loss to the airline market at large is likely (e.g. due to trip mode substitution, trip consolidation, trip replacement (e.g. teleconference) or cancellation). In this report, 10% of the soft costs are considered **scalable** in this way. Whilst both the hard costs and soft costs vary as a function of many variables, we have used estimates of the European average, due to lack of better data.

Returning to the value of time, this also varies as a function of many variables: by country, person, mode (air normally being the highest) and by journey distance and purpose (business-purpose usually being the highest). It also varies by the *stage* of the journey. One source in [4] assumes the value of time for delays, in particular, is 50% higher than for travel time *per se*, and also cites values for the waiting time between departures. In addition to delay, waiting and interchange times, other studies have differentiated between: access time, in-vehicle and out-of-vehicle time, headway (service frequency) and departure time shift (schedule delay), and other values of time which apply to specific modes [41].

Ball et al. [21] have calculated costs to passengers due to: delay and disruption (through simulations using detailed passenger itinerary and flight delay data); passenger inconvenience resulting from (airport capacity-induced) schedule delay (through statistical analysis and optimisation to find differences between capacity-constrained and ideal schedules); and 'schedule adjustment' costs (adapting personal travel schedules to mitigate delay impacts). Through econometric modelling these authors also calculate 'lost demand' costs such as welfare losses due to suppression of demand in delay-impacted markets and modal shift. These calculations thus cover both value of time and soft costs.

The value of time is widely used in cost-benefit analyses for planning improvements in transport services and infrastructure, which deliver improved (usually faster) services to the traveller. The value of time corresponds to an estimate of the 'non-monetary' cost associated with a journey. When this is added to the monetary cost[22], this produces the generalised cost[23].

The value of time is itself often split into work-related and non-work-related time. The former relates to trips undertaken as part of the traveller's work. It is often simply assessed as non-productive ('wasted') time, i.e. an opportunity cost to the employer (generally equivalent to the worker's rate of pay, with on-costs). More accurate assessments may take into account the amount of productive time during the trip (e.g. working on-board an aircraft, or in an airport lounge during a delay).

It is more difficult to assign a value to non-working time. This is associated with the concept of 'utility[24] theory' and is usually estimated from 'revealed preference' or 'stated preference' analysis techniques. These respectively analyse real, and hypothetical, traveller choices, typically as a function of the speed, cost (and sometimes reliability) of different travel choices / modes.

Although we have not included the value of time in these calculations, we can outline the general effect on costs were it to be included. A more detailed commentary is beyond the scope of this report. The **value of time** values cited in EUROCONTROL's 'Standard Inputs' [4], range from **€43 - €55** per hour, per passenger (for the preferred source; examples of wider ranges are also discussed). From Section 3.6, adding together the delay-weighted average hard and soft costs (10% of latter), gives a **scalable** passenger cost *to the airline* of around **€12** per hour, per passenger. This value can be multiplied over a network or a time period.

Using the soft cost at 100% gives a **single-flight**, passenger cost *to the airline* of around **€22** per hour, per passenger. *Prima facie*, even with single-flight costs, the lower estimate of the value of time means that passenger costs approximately **triple** if passenger value of time is added to the direct airline costs associated with passenger delay.

This is a rather crude comparison, however. Whilst the soft and hard costs calculated are strictly related to delay relative to schedule, it is not clear [4] if the €43 - €55 value of time values are marginal values or average values. The value of time is also not cited as a function of delay *duration*, which is an important consideration.

Multiplying the hard costs over a network or a period of time is appropriate, whereas there are uncertainties relating to the adjustment necessary when similarly scaling-up either the soft costs or values of time. The scalability of soft costs is constrained by air transport market shares; values of time may be adjusted by travellers as a direct result of experiencing delay. Further research is required before these important questions may be resolved.

[22] Actual 'out-of-pocket' costs: for a trip by air, the 'gate-to-gate' monetary cost is the air fare (including taxes), whilst the full origin-destination cost usually includes the cost of other transportation modes before and after the leg by air.

[23] Generalised costs are equivalent to the price of a good, as used with price elasticities in the context of the theory of supply (airline capacity) and demand.

[24] In simple terms, the desirability of consuming a good or service, or the satisfaction derived therefrom. It is a relative measure.

Annex D
Single-flight cost-benefit trade-off tables

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).

For the calculations elsewhere in this report, 10% of the soft costs in Table 18 are used. Table D1 and Table D2, however, present tactical costs (without reactionary delay) for selected at-gate and en-route delays, with *full* soft costs. These values may be used to calculate single-flight trade-offs, i.e. costs for a specific tactical decision.

Table D1. AT-GATE / BASE / primary tactical costs

Delay (mins)	5	15	30	60	90	120
B733	80	460	1 660	6 790	13 330	19 950
B734	90	500	1 860	7 700	15 150	22 700
B735	80	410	1 500	6 100	11 960	17 900
B738	100	550	2 060	8 540	16 800	25 170
B752	110	650	2 490	10 450	20 630	30 950
B763	160	960	3 680	15 500	30 620	45 940
B744	220	1 360	5 250	22 270	44 040	66 110
A319	80	460	1 700	7 060	13 890	20 810
A320	90	510	1 930	8 070	15 900	23 840
A321	100	600	2 300	9 720	19 210	28 820
AT43	40	200	640	2 460	4 740	7 060
AT72	50	250	850	3 350	6 510	9 710

Euros, total (2010). Without reactionary costs, ***with full soft cost****.*

Table D2. EN-ROUTE / BASE / primary tactical costs

Delay (mins)	5	15	30	60	90	120
B733	220	870	2 480	8 440	15 790	23 230
B734	220	910	2 680	9 340	17 610	25 980
B735	200	790	2 250	7 600	14 210	20 900
B738	240	970	2 900	10 230	19 340	28 560
B752	290	1 200	3 590	12 660	23 940	35 360
B763	420	1 740	5 240	18 620	35 300	52 180
B744	740	2 930	8 390	28 550	53 470	78 670
A319	210	850	2 490	8 630	16 250	23 960
A320	220	910	2 730	9 660	18 290	27 030
A321	260	1 070	3 250	11 610	22 040	32 590
AT43	70	280	820	2 800	5 260	7 750
AT72	90	370	1 090	3 830	7 230	10 670

Euros, total (2010). Without reactionary costs, ***with full soft cost****.*

Table D3. Re-route example for a B738

Case	Dep.	Arr.	Cost of delay components	Source	Cost (EUR)
Schedule	1500	1600	n/a	n/a	0
ATFM slot	1530	1630	30 mins at-gate	Table D1	**2 060**
Alternative	1510	1615	10 mins maintenance (at-gate)	Table 13	4
			15 mins crew	Table 16	135
			15 mins passenger hard	Tables 17, B2	254
			15 mins passenger soft	Tables 18, B2	163
		en-route	*5 mins maintenance (en-route)*	Table 15	14
		extension cost	*5 mins fuel (en-route)*	Tables 1, F2	129
			Total for alternative		**699**
ATFM slot - Alternative			Difference		**1 361**

Table D3 gives a simplified example of how the costs in this report may be used to calculate the trade-off between an ATFM slot delay and the alternative choice (re-route) of a reduced slot delay associated with a longer en-route time. The ATFM slot is 30 minutes later than the scheduled time. Under the assumption of the same route being flown and no en-route recovery, the cost of this delay is simply read from Table D1 for the B738.

The alternative (re-route) has an ATFM slot brought forward by 20 minutes to 1510. This is still 10 minutes later than scheduled, so the aircraft spends 10 minutes longer at the gate. It arrives at 1615, 15 minutes later than scheduled, thus incurring 15 minutes of extra crew and passenger costs (full soft costs used). The en-route time is 5 minutes longer than scheduled (65 minutes), thus incurring 5 extra minutes of en-route fuel and maintenance costs. (Note that this en-route extension cost of EUR 143, may also be obtained by subtracting the B738 value for 5 minutes' delay in Table D1 from the corresponding value in Table D2, since the only difference between these values are the maintenance and fuel costs. The small difference (EUR 3) is due to various roundings across the tables used). The result of accepting the alternative (re-route) is a saving of EUR 1 361. In examples where this value is very small, or negative, it would not normally be appropriate to accept the re-route.

This is a simplification in various respects. Firstly, it uses primary delay only, as a means of focusing the scope of the calculation (on *average*, we could expect the reactionary effects to further favour the alternative route, in terms of the earlier arrival time, by over EUR 300). Secondly, it ignores unpredictabilities such as taxi times and en-route weather, potential airline priorities such as airport curfews and crew hour constraints, and local experience about slot improvement likelihoods (for a discussion, see [1]). Thirdly, no account is made of accelerated fuel burn to recover the delay, nor any comparison made with a 1530 departure with accelerated fuel burn. For a discussion and quantified example of this (dynamic cost indexing), see [11]. See also Section 5 regarding future research in this area.

Annex E
Exchange rate & inflation data

This annex cites Euro / US Dollar exchange rates and generic European inflation data.

Inflation data are used to inflate general costs, such as the provision of passenger care. Specific inflationary effects are used for the crew and maintenance cost models, not the generic values below. The inflation data are sourced from EUROSTAT (the statistical office of the European Union) and refer to the 'Euro area' data. The Member States of the Euro area are: Belgium, Germany, Ireland, Greece, Spain, France, Italy, Cyprus, Luxembourg, Malta, the Netherlands, Austria, Portugal, Slovenia, Slovakia and Finland. Euro area inflation is measured by the Monetary Union Index of Consumer Prices (MUICP) as defined in Council Regulation (EC) No 2494/95 (of 23 October 1995), which is the official Euro area aggregate. New Member States are integrated into the MUICP using a chain index formula.

Table E1. 'Euro area' annual inflation

Year	Annual inflation
2002	2.2
2003	2.1
2004	2.1
2005	2.2
2006	2.2
2007	2.1
2008	3.3
2009	0.9 [a]
2010	0.9 [b]

[a] Eurostat 'flash estimate', released 05 January 2010

[b] 2009 value used to estimate value for 2010.

http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home

Table E2. US Dollar/Euro reference exchange rates

Year	Exchange rate *(EUR1.00 = USD:)*
2002	0.9456
2003	1.1312
2004	1.2439
2005	1.2441
2006	1.2556
2007	1.3705
2008	1.4708
2009	1.3948

US Dollar/Euro rates cited are reference exchange rates sourced from the European Central Bank's Statistical Data Warehouse:

http://sdw.ecb.europa.eu

Annex F
Fuel burn data

Taxi fuel burn

The ICAO Aircraft Engine Emissions Databank contains reference data by engine for the LTO cycle (take-off; climb out; approach; taxi/ground idle). The taxi/ground idle phase reports fuel burn with a 7% thrust setting. Since the ICAO Databank lists data for jet engines only, turboprop fuel burn data have been sourced directly from the engine supplier, Pratt & Whitney Canada.

Table F1. Taxi fuel burn per minute by aircraft type

Aircraft	Engine	Fuel burn (kg/minute)
B733	CFM56-3-B1	13.7
B734	CFM56-3C-1	14.9
B735	CFM56-3C-1	14.9
B738	CFM56-7B26	13.6
B752	RB211-535E4	21.6
B763	PW4060	25.6
B744	CF6-80C2B1F	47.8
A319	CFM56-5B6/P	11.6
A320	V2527-A5	15.4
A321	CFM56-5B3/P	13.8
AT43	PW120	5.1
AT72	PW124-B	6.1

Sources: ICAO Aircraft Engine Emissions Databank (jets)
Pratt & Whitney Canada (turboprops)

Cruise fuel burn

Table F2 shows the *average* fuel flow in typical cruise with a 65% load factor [1], as calculated by Lufthansa Systems (using the application now known as Lido/Flight). Calculations of additional, *marginal* fuel consumption for increased flight time often gave very similar values (to within 10% for half of the aircraft).

Marginal fuel consumption depends on the total distance flown and compares fuel use for the entire trajectory compared with an associated increase of, say, 1NM. Under the assumption of no altitude constraints, this increase has the same impact, irrespective of where it takes place (climb, descent, en-route phase). When this marginal method is refined, such data will be used, although large changes relative to Table F2 should not be expected.

Table F2. En-route (cruise) fuel burn per minute by aircraft type

Aircraft	Fuel burn (kg/minute)
B733	40.6
B734	40.2
B735	37.1
B738	42.9
B752	55.2
B763	78.8
B744	163.5
A319	38.4
A320	39.3
A321	46.5
AT43	7.2
AT72	10.5

Source: [1]

Arrival management fuel burn

For all jets, Table F3 assumes linear holding between FL50 and FL100. The average fuel burn rates between these flight levels have been calculated using BADA tables for flight durations within 10%, or 10 minutes, of those in Table B1. The fuel carriage penalty estimates the additional fuel consumption of carrying the fuel used during holding, from the origin to the point of holding (a value of 4% per flight-hour was computed [10]: see also Section 2.2.4). Taking into account the longer flight duration operated by the widebody aircraft (B763 >6 hours, B744 >8 hours), the fuel carriage penalty for these aircraft has been halved to avoid over-estimation. For the ATRs, performance data manuals from the manufacturer were consulted under similar assumptions (7500 ft pressure altitude) to interpolate fuel burn (a fuel carriage penalty was similarly applied [10]).

Table F3. Arrival management fuel burn per minute by aircraft type

Aircraft	Average fuel burn FL50-FL100 (kg/minute)	Fuel carriage penalty (kg/minute)	Widebody fuel carriage penalty adjustment	Final, holding fuel burn (kg/minute)
B733	29.4	1.8		31.2
B734	34.9	2.4		37.2
B735	24.2	1.4		25.6
B738	34.9	2.7		37.6
B752	36.9	5.3		42.3
B763	63.0	17.2	-50%	71.6
B744	91.4	31.0	-50%	106.9
A319	31.9	2.0		33.8
A320	35.9	2.5		38.4
A321	38.4	3.0		41.5
AT43	6.7	0.4		7.1
AT72	8.4	0.4		8.8

Sources: Average fuel burns - BADA (jets); [45, 46] (turboprops)

Annex G
Low and high cost scenario primary tactical costs

Table G1. AT-GATE / LOW / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	20	120	410	1 440	2 950	4 870	9 880	16 350	24 200
B734	20	140	470	1 650	3 380	5 580	11 320	18 740	27 730
B735	20	110	370	1 300	2 660	4 380	8 880	14 700	21 760
B738	20	150	520	1 820	3 740	6 180	12 530	20 740	30 700
B752	30	190	650	2 280	4 670	7 710	15 640	25 890	38 320
B763	40	260	900	3 180	6 530	10 780	21 860	36 170	53 540
B744	60	380	1 310	4 600	9 430	15 570	31 550	52 210	77 260
A319	20	120	430	1 520	3 120	5 150	10 430	17 270	25 560
A320	20	140	500	1 750	3 580	5 910	11 980	19 830	29 360
A321	30	170	610	2 130	4 370	7 220	14 640	24 240	35 880
AT43	10	40	140	490	1 000	1 650	3 340	5 520	8 170
AT72	10	60	190	680	1 400	2 300	4 670	7 720	11 430

Euros, total (2010). Without reactionary costs.

Table G2. AT-GATE / HIGH / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	130	580	1 630	5 020	9 670	15 340	29 600	47 610	69 150
B734	140	620	1 790	5 610	10 880	17 310	33 550	54 090	78 680
B735	130	540	1 500	4 580	8 790	13 900	26 750	42 950	62 310
B738	150	690	1 980	6 190	12 020	19 130	37 080	59 800	87 010
B752	160	760	2 270	7 310	14 370	23 010	44 930	72 760	106 160
B763	260	1 120	3 170	9 740	18 780	29 760	57 430	92 360	134 130
B744	350	1 540	4 420	13 770	26 700	42 440	82 180	132 420	192 570
A319	120	560	1 610	5 070	9 870	15 730	30 540	49 290	71 750
A320	130	620	1 810	5 750	11 230	17 920	34 860	56 340	82 090
A321	150	700	2 100	6 780	13 340	21 380	41 790	67 720	98 850
AT43	70	280	720	2 050	3 810	5 910	11 120	17 610	25 310
AT72	90	340	910	2 650	5 000	7 820	14 860	23 670	34 150

Euros, total (2010). Without reactionary costs.

Table G3. TAXI / LOW / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	50	220	600	1 830	3 540	5 650	11 050	17 900	26 140
B734	60	240	680	2 080	4 030	6 440	12 610	20 450	29 880
B735	50	210	580	1 720	3 290	5 220	10 140	16 380	23 860
B738	50	240	710	2 200	4 310	6 930	13 660	22 250	32 580
B752	80	340	950	2 880	5 580	8 920	17 450	28 300	41 330
B763	100	440	1 270	3 910	7 620	12 230	24 040	39 080	57 180
B744	170	720	2 000	5 980	11 490	18 320	35 670	57 700	84 130
A319	50	210	600	1 860	3 630	5 830	11 460	18 640	27 270
A320	60	250	720	2 180	4 240	6 790	13 300	21 590	31 550
A321	60	280	810	2 540	4 990	8 040	15 870	25 870	37 920
AT43	20	80	220	650	1 240	1 960	3 810	6 150	8 960
AT72	20	100	290	870	1 680	2 680	5 230	8 480	12 370

Euros, total (2010). Without reactionary costs.

Table G4. TAXI / HIGH / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	200	780	2 040	5 840	10 910	16 980	32 070	50 900	73 260
B734	210	850	2 240	6 500	12 220	19 100	36 220	57 650	83 140
B735	200	760	1 940	5 440	10 090	15 640	29 360	46 430	66 660
B738	220	890	2 380	7 000	13 240	20 750	39 520	63 050	91 060
B752	260	1 070	2 890	8 560	16 240	25 500	48 660	77 740	112 380
B763	390	1 510	3 930	11 270	21 080	32 830	62 030	98 490	141 800
B744	570	2 200	5 730	16 390	30 620	47 670	90 020	142 880	205 650
A319	180	740	1 980	5 810	10 970	17 200	32 740	52 220	75 420
A320	210	850	2 280	6 680	12 620	19 780	37 660	60 070	86 750
A321	220	910	2 520	7 630	14 620	23 090	44 350	71 130	103 110
AT43	100	360	890	2 380	4 310	6 580	12 120	18 950	26 990
AT72	120	440	1 110	3 050	5 600	8 620	16 050	25 260	36 140

Euros, total (2010). Without reactionary costs.

Table G5. EN-ROUTE / LOW / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	110	380	940	2 500	4 540	6 990	13 050	20 580	29 490
B734	110	400	1 000	2 710	4 980	7 710	14 510	22 980	33 040
B735	100	350	860	2 270	4 120	6 330	11 800	18 590	26 620
B738	110	420	1 070	2 920	5 390	8 380	15 830	25 140	36 200
B752	150	540	1 360	3 710	6 820	10 580	19 950	31 630	45 490
B763	210	770	1 930	5 230	9 590	14 860	27 980	44 350	63 760
B744	410	1 440	3 430	8 840	15 780	24 040	44 250	69 140	98 430
A319	100	380	940	2 530	4 630	7 170	13 470	21 310	30 610
A320	110	400	1 010	2 780	5 130	7 980	15 090	23 970	34 530
A321	130	480	1 220	3 360	6 210	9 670	18 310	29 130	41 990
AT43	20	90	250	700	1 320	2 080	3 980	6 380	9 240
AT72	30	130	350	990	1 850	2 910	5 580	8 940	12 950

Euros, total (2010). Without reactionary costs.

Table G6. EN-ROUTE / HIGH / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	310	1 120	2 720	7 190	12 940	19 690	36 130	56 320	80 030
B734	320	1 170	2 880	7 770	14 130	21 650	40 050	62 760	89 520
B735	290	1 030	2 490	6 560	11 770	17 870	32 710	50 890	72 240
B738	340	1 260	3 120	8 470	15 440	23 690	43 920	68 920	98 400
B752	400	1 490	3 730	10 230	18 750	28 850	53 690	84 440	120 760
B763	610	2 170	5 260	13 930	25 070	38 150	70 010	109 130	155 090
B744	1 040	3 610	8 560	22 060	39 130	59 020	107 040	165 570	234 010
A319	300	1 080	2 660	7 160	13 000	19 910	36 800	57 640	82 190
A320	310	1 150	2 880	7 890	14 440	22 200	41 290	64 910	92 800
A321	350	1 320	3 340	9 280	17 090	26 370	49 280	77 700	111 330
AT43	110	390	950	2 500	4 480	6 810	12 470	19 410	27 560
AT72	140	500	1 230	3 290	5 950	9 090	16 760	26 210	37 320

Euros, total (2010). Without reactionary costs.

Table G7. ARRIVAL MGT / LOW / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	90	330	830	2 270	4 200	6 540	12 370	19 680	28 360
B734	100	380	960	2 640	4 870	7 560	14 290	22 700	32 680
B735	70	280	720	1 990	3 700	5 780	10 980	17 490	25 240
B738	100	390	1 000	2 800	5 200	8 120	15 450	24 630	35 560
B752	120	470	1 210	3 400	6 360	9 960	19 020	30 390	43 950
B763	190	730	1 840	5 050	9 330	14 520	27 470	43 650	62 890
B744	290	1 100	2 750	7 480	13 750	21 320	40 180	63 710	91 640
A319	90	350	880	2 420	4 470	6 950	13 130	20 870	30 060
A320	100	400	1 000	2 760	5 100	7 940	15 020	23 890	34 420
A321	120	450	1 160	3 240	6 030	9 430	17 950	28 650	41 390
AT43	20	90	250	700	1 320	2 070	3 970	6 370	9 230
AT72	30	120	330	950	1 790	2 830	5 460	8 780	12 750

Euros, total (2010). Without reactionary costs.

Table G8. ARRIVAL MGT / HIGH / primary tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	280	1 010	2 490	6 740	12 260	18 790	34 780	54 510	77 780
B734	310	1 130	2 810	7 630	13 920	21 360	39 620	62 180	88 800
B735	250	900	2 220	6 010	10 940	16 770	31 050	48 690	69 480
B738	320	1 190	2 990	8 210	15 060	23 180	43 160	67 900	97 130
B752	350	1 330	3 420	9 620	17 820	27 610	51 830	81 960	117 660
B763	580	2 080	5 090	13 590	24 550	37 460	68 970	107 750	153 360
B744	810	2 940	7 210	19 340	35 050	53 580	98 890	154 700	220 430
A319	280	1 020	2 540	6 940	12 670	19 460	36 140	56 760	81 090
A320	310	1 140	2 860	7 850	14 370	22 120	41 160	64 730	92 580
A321	330	1 260	3 220	9 040	16 730	25 890	48 560	76 740	110 130
AT43	110	390	950	2 490	4 470	6 800	12 450	19 390	27 540
AT72	130	480	1 190	3 210	5 830	8 930	16 520	25 880	36 910

Euros, total (2010). Without reactionary costs.

Annex H
Low and high cost scenario full tactical (with reactionary) costs

Table H1. AT-GATE / LOW / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	20	140	510	2 190	5 690	10 730	16 130	23 470	32 960
B734	20	160	580	2 500	6 520	12 270	18 400	26 700	37 330
B735	20	120	460	1 970	5 130	9 660	14 550	21 240	29 940
B738	20	170	640	2 760	7 210	13 580	20 310	29 400	41 000
B752	30	210	800	3 460	8 990	16 910	25 230	36 350	50 420
B763	40	320	1 260	6 060	17 000	36 960	54 120	69 310	88 320
B744	70	460	1 830	8 740	24 500	53 250	77 860	99 400	126 090
A319	20	140	530	2 310	6 020	11 330	17 000	24 710	34 640
A320	20	160	620	2 650	6 900	12 990	19 450	28 170	39 340
A321	30	190	750	3 230	8 410	15 840	23 650	34 120	47 400
AT43	10	50	170	750	1 960	3 720	5 800	8 850	13 140
AT72	10	70	240	1 040	2 720	5 140	7 900	11 820	17 170

Euros, total (2010). With reactionary costs.

Table H2. AT-GATE / HIGH / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	90	590	2 310	11 660	32 490	63 910	79 190	99 480	125 360
B734	100	650	2 580	13 180	36 870	72 360	89 610	112 440	141 370
B735	90	540	2 100	10 560	29 340	57 820	71 680	90 160	113 860
B738	110	720	2 850	14 550	40 730	79 890	98 860	123 860	155 410
B752	120	840	3 380	17 560	49 510	96 730	119 670	149 780	187 520
B763	350	1 660	5 510	24 600	65 830	141 700	193 530	230 750	276 860
B744	470	2 270	7 670	34 840	93 840	202 670	276 730	329 250	393 740
A319	90	590	2 340	11 990	33 630	65 980	81 800	102 830	129 640
A320	100	670	2 650	13 670	38 410	75 220	93 180	116 940	147 030
A321	120	780	3 140	16 340	46 110	90 060	111 490	139 700	175 170
AT43	40	250	930	4 490	12 220	24 490	30 710	39 480	51 520
AT72	60	320	1 210	5 930	16 310	32 450	40 500	51 600	66 420

Euros, total (2010). With reactionary costs.

Table H3. TAXI / LOW / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	50	240	700	2 580	6 280	11 510	17 300	25 020	34 900
B734	60	260	790	2 930	7 170	13 130	19 690	28 410	39 480
B735	50	220	670	2 390	5 760	10 500	15 810	22 920	32 040
B738	50	260	830	3 140	7 780	14 330	21 440	30 910	42 880
B752	80	360	1 100	4 060	9 900	18 120	27 040	38 760	53 430
B763	100	500	1 630	6 790	18 090	38 410	56 300	72 220	91 960
B744	180	800	2 520	10 120	26 560	56 000	81 980	104 890	132 960
A319	50	230	700	2 650	6 530	12 010	18 030	26 080	36 350
A320	60	270	840	3 080	7 560	13 870	20 770	29 930	41 530
A321	60	300	950	3 640	9 030	16 660	24 880	35 750	49 440
AT43	20	90	250	910	2 200	4 030	6 270	9 480	13 930
AT72	20	110	340	1 230	3 000	5 520	8 460	12 580	18 110

Euros, total (2010). With reactionary costs.

Table H4. TAXI / HIGH / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	160	790	2 720	12 480	33 730	65 550	81 660	102 770	129 470
B734	170	880	3 030	14 070	38 210	74 150	92 280	116 000	145 830
B735	160	760	2 540	11 420	30 640	59 560	74 290	93 640	118 210
B738	180	920	3 250	15 360	41 950	81 510	101 300	127 110	159 460
B752	220	1 150	4 000	18 810	51 380	99 220	123 400	154 760	193 740
B763	480	2 050	6 270	26 130	68 130	144 770	198 130	236 880	284 530
B744	690	2 930	8 980	37 460	97 760	207 900	284 570	339 710	406 820
A319	150	770	2 710	12 730	34 730	67 450	84 000	105 760	133 310
A320	180	900	3 120	14 600	39 800	77 080	95 980	120 670	151 690
A321	190	990	3 560	17 190	47 390	91 770	114 050	143 110	179 430
AT43	70	330	1 100	4 820	12 720	25 160	31 710	40 820	53 200
AT72	90	420	1 410	6 330	16 910	33 250	41 690	53 190	68 410

Euros, total (2010). With reactionary costs.

Table H5. EN-ROUTE / LOW / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	110	400	1 040	3 250	7 280	12 850	19 300	27 700	38 250
B734	110	420	1 110	3 560	8 120	14 400	21 590	30 940	42 640
B735	100	360	950	2 940	6 590	11 610	17 470	25 130	34 800
B738	110	440	1 190	3 860	8 860	15 780	23 610	33 800	46 500
B752	150	560	1 510	4 890	11 140	19 780	29 540	42 090	57 590
B763	210	830	2 290	8 110	20 060	41 040	60 240	77 490	98 540
B744	420	1 520	3 950	12 980	30 850	61 720	90 560	116 330	147 260
A319	100	400	1 040	3 320	7 530	13 350	20 040	28 750	39 690
A320	110	420	1 130	3 680	8 450	15 060	22 560	32 310	44 510
A321	130	500	1 360	4 460	10 250	18 290	27 320	39 010	53 510
AT43	20	100	280	960	2 280	4 150	6 440	9 710	14 210
AT72	30	140	400	1 350	3 170	5 750	8 810	13 040	18 690

Euros, total (2010). With reactionary costs.

Table H6. EN-ROUTE / HIGH / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	270	1 130	3 400	13 830	35 760	68 260	85 720	108 190	136 240
B734	280	1 200	3 670	15 340	40 120	76 700	96 110	121 110	152 210
B735	250	1 030	3 090	12 540	32 320	61 790	77 640	98 100	123 790
B738	300	1 290	3 990	16 830	44 150	84 450	105 700	132 980	166 800
B752	360	1 570	4 840	20 480	53 890	102 570	128 430	161 460	202 120
B763	700	2 710	7 600	28 790	72 120	150 090	206 110	247 520	297 820
B744	1 160	4 340	11 810	43 130	106 270	219 250	301 590	362 400	435 180
A319	270	1 110	3 390	14 080	36 760	70 160	88 060	111 180	140 080
A320	280	1 200	3 720	15 810	41 620	79 500	99 610	125 510	157 740
A321	320	1 400	4 380	18 840	49 860	95 050	118 980	149 680	187 650
AT43	80	360	1 160	4 940	12 890	25 390	32 060	41 280	53 770
AT72	110	480	1 530	6 570	17 260	33 720	42 400	54 140	69 590

Euros, total (2010). With reactionary costs.

Table H7. ARRIVAL MGT / LOW / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	90	350	930	3 020	6 940	12 400	18 620	26 800	37 120
B734	100	400	1 070	3 490	8 010	14 250	21 370	30 660	42 280
B735	70	290	810	2 660	6 170	11 060	16 650	24 030	33 420
B738	100	410	1 120	3 740	8 670	15 520	23 230	33 290	45 860
B752	120	490	1 360	4 580	10 680	19 160	28 610	40 850	56 050
B763	190	790	2 200	7 930	19 800	40 700	59 730	76 790	97 670
B744	300	1 180	3 270	11 620	28 820	59 000	86 490	110 900	140 470
A319	90	370	980	3 210	7 370	13 130	19 700	28 310	39 140
A320	100	420	1 120	3 660	8 420	15 020	22 490	32 230	44 400
A321	120	470	1 300	4 340	10 070	18 050	26 960	38 530	52 910
AT43	20	100	280	960	2 280	4 140	6 430	9 700	14 200
AT72	30	130	380	1 310	3 110	5 670	8 690	12 880	18 490

Euros, total (2010). With reactionary costs.

Table H8. ARRIVAL MGT / HIGH / full tactical costs

Delay (mins)	5	15	30	60	90	120	180	240	300
B733	240	1 020	3 170	13 380	35 080	67 360	84 370	106 380	133 990
B734	270	1 160	3 600	15 200	39 910	76 410	95 680	120 530	151 490
B735	210	900	2 820	11 990	31 490	60 690	75 980	95 900	121 030
B738	280	1 220	3 860	16 570	43 770	83 940	104 940	131 960	165 530
B752	310	1 410	4 530	19 870	52 960	101 330	126 570	158 980	199 020
B763	670	2 620	7 430	28 450	71 600	149 400	205 070	246 140	296 090
B744	930	3 670	10 460	40 410	102 190	213 810	293 440	351 530	421 600
A319	250	1 050	3 270	13 860	36 430	69 710	87 400	110 300	138 980
A320	280	1 190	3 700	15 770	41 550	79 420	99 480	125 330	157 520
A321	300	1 340	4 260	18 600	49 500	94 570	118 260	148 720	186 450
AT43	80	360	1 160	4 930	12 880	25 380	32 040	41 260	53 750
AT72	100	460	1 490	6 490	17 140	33 560	42 160	53 810	69 180

Euros, total (2010). With reactionary costs.

Annex I
Schedule buffer cost-benefit trade-off

This annex compares the strategic costs of Section 2 with the tactical costs of Section 3 to estimate the cost-benefit of adding schedule buffer to a timetable. We demonstrate a simplified example with fixed inbound delay.

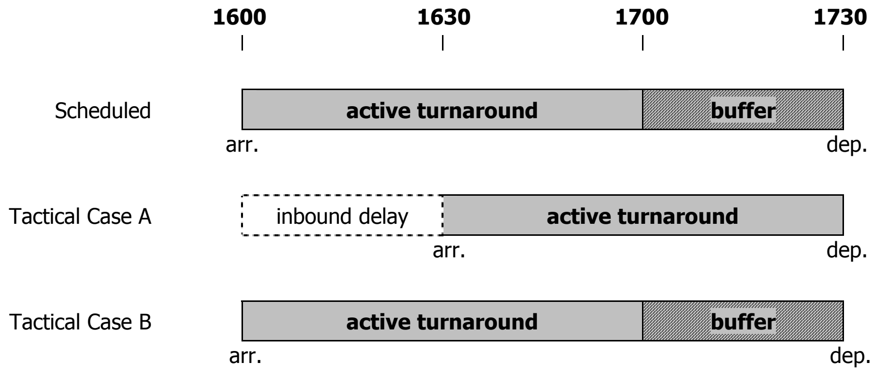

Figure I1. Schedule buffer and tactical delay

The scheduled case in Figure I1 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, 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.

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. 30 minutes of new delay have thus been avoided by the presence of the buffer. What is the cost associated with these 30 minutes of new delay? We could treat them as just the additional reactionary costs of Section 3.7. However, these costs are *conditional* on the amount of existing buffer, averaged over all European operations. They thus underestimate the true without-buffer cost because they have *already been reduced* by buffers, *including* the recovery in Case A between the inbound and outbound flight.

We will thus treat the 30 minutes of new delay avoided as a primary delay, without any reactionary effect. This allows a decoupling of the dependencies between the *a priori* strategic trade-off and the effect of (other) existing buffers. By not including reactionary costs associated with the primary cost, we are assuming that buffer trade-offs elsewhere are also, at the strategic phase, designed to substantially mitigate reactionary effects (a point to which we shall return in a moment). The true trade-off is more complex than this, but the simplification made allows a transparent calculation.

30 minutes is selected as our example as an intermediate level of delay. If the inbound delay under consideration were to be particularly small, say in the region of 5 minutes, it would make less sense to formally assess the need for buffer, since the cost of the 5 minutes is low and small delays could almost always be recovered through a reduced turnaround time in any case. Buffers need to be large enough to absorb delays that are likely to have operational consequences. The *a priori* assumption that existing buffers successfully mitigate reactionary effects is actually not a strong assumption

because high levels of tactical delay will inevitably cause reactionary effects on the day of operations, as buffers are rarely able to absorb them (all). For this reason, we do not use a high inbound delay in the example.

In Table 19, it may be observed that 30 minutes of primary delay may be considered as a type of equilibrium point at which the reactionary delay just starts to be equal to the primary delay (the value of the multiplier, 1.94, is just under 2). On *average*, 30 minutes of primary delay produces another 30 minutes of delay in the network, so the net effect is no recovery. The main point, however, is that 30 minutes is neither a particularly large nor small delay.

Not only do we simplify the calculation by comparing the 30 minutes of strategic buffer with 30 minutes of new primary delay (and no reactionary delay) but a further simplification (probably of less impact) is also made regarding the inbound delay. Some of the passengers onboard the inbound aircraft may be transferring onto other flights affected by the inbound delay (they could even be on its next rotation). In specific cases such as this, some passenger costs to the airline might be higher than those associated with the inbound 30 minutes of delay, some may be lower. As discussed in Section 3.7, there may also be some crew cost recoveries in Case A. These have also been neglected in the calculation, by treating the inbound and outbound costs as independent (for a 30 minute base scenario, such cost recoveries average only 2% of the total primary effect for narrowbodies; there is no such effect for widebodies). For rather large buffers, it would in theory 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.

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 are fixed by the scheduled departure time of 1730. (A whole range of inbound delays, less than and greater than 30 minutes, and sometimes even early arrivals, occur tactically.)

Cost-benefit trade-off. Mindful of the limitations of the foregoing simplifications, they nevertheless allow transparent calculations to be made. Table I1 illustrates some examples using 30 minutes of buffer. Taking the first row as an example, the 30 minutes of tactical delay avoided saves EUR 1 230 (Table 22), whereas the buffer costs EUR 510 (Table 9). If this delay is expected on at least 41% of occasions, the buffer is cost effective (net expected cost, EUR: 510 x 1.0 (every occasion) - 1 230 x 0.41 $\cong$ 0). With a 30 minute buffer and a 60 minute inbound delay, resulting in a new 30 minute delay instead of 60 minutes, the Case A saving is EUR 4 010 - 1 230 = 2 780 (Table 22), and, logically, this requires a lower expected frequency (at least 18%) to 'break even' (net expected cost $\cong$ 0). Lower minimum expected frequencies (Table I1) are required for a B744 - i.e. the tactical/strategic cost ratios are higher for widebodies.

Table I1. Minimum expected (break even) frequencies for 30 minutes of buffer

Aircraft	Inbound delay (mins)	Outbound delay (mins)	Break even frequency of inbound delay
B738	30	0	41%
B738	60	30	18%
B744	30	0	36%
B744	60	30	15%

All values in Table I1 are calculated using base cost scenarios. The same principles apply to other aircraft, cost scenarios and intermediate delay magnitudes. Ball et al. [21] estimate schedule buffer costs (using less impeded block times) that are similar to their tactical cost estimates (see also Section 2.1.6). This simple, binary example with fixed delay is extended to a treatment of variable inbound delay in [48], stressing the importance of predictability. For a discussion of robust scheduling, see [49].

Annex J
Regression analysis on full tactical delay cost

Objective. This annex serves two functions. Firstly, it explores the relationship between the total tactical cost of delay and other variables (passenger numbers and MTOW). This is to enable interpolation and extrapolation for other aircraft, such that estimates of delay costs can be made for aircraft not included in the core set (B733, B734, B735, B738, B752, A319, A320, A321, AT43, AT72, B744 and B763). Various fits are explored and the logic of each briefly examined. Secondly, these fits are used to calculate wider European ATFM delay costs, by extending the coverage of the calculations to other aircraft.

Technical note. Linear regression (least squares) is used and all coefficients shown in the tables were calculated using SPSS. The regressions are of the form y = mx + c, where y is the cost and x is either the number of passengers or a function of MTOW. Passenger numbers and MTOW values are taken from Table B2. All scenarios are base cost scenarios, using the full tactical costs of Table 26 and Table 28. Some degree of caution should be exercised in using such fits, although the high r^2 (sample coefficient of determination) values across the range of core aircraft (from the AT43 to the 23-fold heavier B744, see Table B2) suggests a certain degree of robustness.

Regression fits. Tables J1 and J2 show that the full cost of tactical delay (i.e. including reactionary costs) is modelled very well (minimum r^2 = 0.960) by passenger numbers, both at-gate and en-route. This is to be expected, since these costs are often dominated by the passenger costs, as detailed in Section 4. This domination is greatest at higher delay, which contributes to the slightly higher r^2 values on the right of the tables. As expected, the gradients (m) are higher for the en-route costs.

Table J1. AT-GATE regression coefficients for full tactical cost v. passenger numbers

Delay (mins)	5	15	30	60	90	120	180	240	300
r^2	0.960	0.990	0.994	0.995	0.996	0.985	0.978	0.985	0.990
m	0.654	3.77	13.7	65.0	177	388	558	682	832
c	-2.11	-2.95	-29.6	-427	-1132	-7048	-12646	-10786	-7472

Base scenario, with reactionary costs.

Table J2. EN-ROUTE regression coefficients for full tactical cost v. passenger numbers

Delay (mins)	5	15	30	60	90	120	180	240	300
r^2	0.965	0.979	0.987	0.993	0.996	0.986	0.980	0.986	0.990
m	2.23	8.52	23.2	83.9	205	426	615	758	927
c	-38.3	-114	-245	-858	-1778	-7915	-13942	-12514	-9639

Base scenario, with reactionary costs.

Whilst these fits are useful for other aircraft (outside the core set), typical passenger numbers are not always readily available for use in other models. MTOW has therefore been explored as an alternative fit. Although a full set of fits has not been explored, polynomial fits suggested √MTOW as a better fit for passenger numbers (r^2 = 0.991) than simple MTOW (r^2 = 0.930), and hence superior for cost regressions.

After the passenger costs of delay to the airline, depending on the delay duration, the next highest contribution is typically fuel costs for the en-route phase (becoming proportionally less as the length of the delay increases - see Section 4.1.11). For the en-route phase, the third largest component of the costs is usually the crew cost, typically the second highest cost at-gate (with engines off).

In addition to the correlation with passenger numbers cited, √MTOW is obviously correlated with the size of the aircraft and thus en-route fuel burn ($r^2 = 0.975$; fuel burn data in Table F2) and, to a less pronounced extent, with the crew costs ($r^2 = 0.880$; base scenario for 15 minutes used, including reactionary effects, calculation not shown). The relationship between aircraft size and crew costs is outlined in Section 2.5. In summary, it is logical that delay costs should be well modelled as a function of MTOW. The regression coefficients for √MTOW are given in Table J3 (at-gate full tactical cost) and Table J4 (en-route full tactical cost). The r^2 values are actually higher than the passenger fits for lower en-route delay durations, and in no case poorer than 0.009 compared with the passenger coefficients. The gradients (*m*) are again higher for the en-route costs and are almost linear in the passenger gradients (the scalar is 19: itself the gradient of the regression between √MTOW and passenger numbers). The at-gate and en-route fits across the twelve aircraft are shown in Figure J1, for a 15 minute delay, as summarised in the second data columns of tables J3 and J4, respectively. Good fits (√MTOW and MTOW, $r^2 \cong 0.95$) are also obtained with the strategic costs (not shown).

Table J3. AT-GATE regression coefficients for full tactical cost v. √MTOW

Delay (mins)	5	15	30	60	90	120	180	240	300
r^2	0.961	0.982	0.986	0.987	0.988	0.977	0.970	0.977	0.981
m	12.5	71.6	260	1233	3358	7371	10583	12942	15781
c	-32.9	-178	-663	-3432	-9315	-25015	-38440	-42327	-45932

Base scenario, with reactionary costs.

Table J4. EN-ROUTE regression coefficients for full tactical cost v. √MTOW

Delay (mins)	5	15	30	60	90	120	180	240	300
r^2	0.984	0.991	0.994	0.993	0.992	0.981	0.975	0.981	0.986
m	42.9	163	443	1599	3907	8104	11683	14408	17614
c	-147	-524	-1348	-4801	-11367	-27759	-42551	-47809	-52793

Base scenario, with reactionary costs.

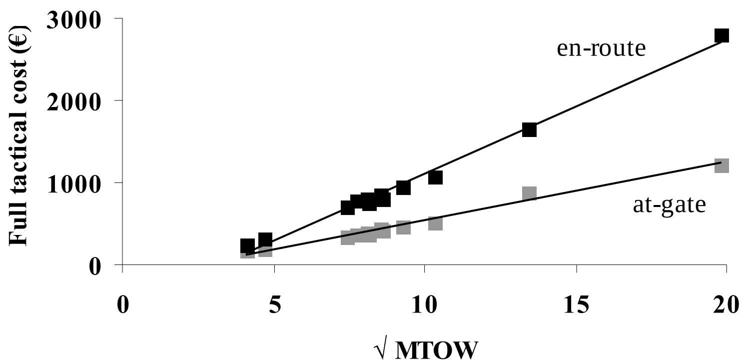

Figure J1. Full tactical cost as a function of √MTOW

It has thus been demonstrated that √MTOW offers, in theory and empirically, a good linear fit for the full tactical cost of delay. The aircraft weight factor used by CRCO for en-route charges is also a linear function of √MTOW, with many airport charges similarly a function of MTOW. Its use in the wider air transport cost-setting environment is thus already established.

ATFM costs – initial estimates using the core aircraft. The next task is to use these fits to calculate the wider European ATFM delay costs, by extending the coverage of the calculations to other aircraft. To develop the calculation, we will firstly use the twelve core aircraft. Weighting the full, at-gate tactical costs of Table 26 by the distribution of ATFM delays these aircraft experience (Table B3), first requires the interpolation[25] of these costs for each delay range in Table J5. This gives the core aircraft costs shown in the second data row. For example, in the 1-4 minutes band, the average cost is EUR 35 across the twelve aircraft, the cost for each aircraft type being weighted by the number of ATFM delay minutes for the type. Multiplying these costs by the proportion of ATFM delays in each band (Table B4) and summing the products, gives an overall weighted average of the cost of delay of an ATFM delayed flight of EUR 1 800 (based on the core aircraft, but as an initial estimate for all aircraft). 748 830 flights (see footnote 21) had some ATFM delay [10]. The total cost of ATFM delay (for all causes and including reactionary costs) may therefore be initially estimated as EUR 1 300 million (multiplying by the weighted average of an ATFM delayed flight of EUR 1 800). Dividing this total cost by the total number of ATFM minutes (15.3 million) gives an indicative value of EUR 88 per minute (again, based on the core twelve aircraft, as an initial estimate for all aircraft).

Table J5. ATFM delay ranges and weighted costs

Delay range (mins)	1 -4	5 -14	15 -29	30 -59	60 -89	90 -119	120 -179	180 -239	240 -299	300+
Proportion of delays	0.045	0.420	0.348	0.152	0.024	0.007	0.004	0.001	0.000[3]	0.000[1]
Core aircraft	35	230	940	4 180	12 890	27 580	42 850	57 420	76 010	86 610
Non-core aircraft	28	180	750	3 330	10 290	22 030	34 220	45 860	60 700	69 170
All aircraft average	32	210	870	3 870	11 940	25 560	39 710	53 220	70 450	80 270

Euros, total (2010). With reactionary costs.

ATFM costs – estimates using all European aircraft. Having established that √MTOW is a good estimate of delay cost, this can be used to estimate the analogous costs in Table J5 for aircraft not part of the core twelve, i.e. the rest of the fleet. The ATFM-weighted (Table B3) √MTOW values (from Table B2) for the core twelve aircraft is 8.6. Performing the same weighting calculation for all other aircraft (data from PRU, MTOWs calculated as per Table B2, calculation not shown) gives a value of 6.9. (The core twelve aircraft, weighted by ATFM delays, are heavier than the European average.) Since √MTOW is linear in cost, the costs in Table J5 for the non-core aircraft (all aircraft apart from the core twelve) are estimated as the core aircraft values multiplied by the ratio 6.9 / 8.6. The final row of Table J5 is the combination of the core and non-core aircraft rows, weighted by the total number of ATFM delay minutes experienced by these two sets of aircraft (Table B3)[26]. Finally, using the same methods for the core aircraft (above), now for all European aircraft, gives the results shown in Table J6. The European network average cost of ATFM delay, per minute, should be used with some caution in an operational context as it is a high-level average.

Table J6. European ATFM delay cost estimates

Factor	Cost
Network total cost of ATFM delay (all causes)	**1 250 million**
Average cost of delay of an ATFM delayed aircraft	**1 660**
Network average cost of ATFM delay, per minute	**81**

Costs in 2010 Euros. Delay weights use 2009 ATFM data.

[25] Linear, polynomial and power fits all gave regression coefficients of over 0.97 but either heavily overestimated costs at low delay, or at high delay. Multiple, simple linear interpolations of the delay magnitudes in Table 26 were thus used to produce estimates for the mid-point of each delay range in Table J5. The cost for the '300+' minutes category is that for 300 minutes.

[26] A more protracted method (calculation not shown) of using the average value of √MTOW across all aircraft (7.99, weighted by total ATFM delay minutes for each aircraft type) in each of the regression fits in Table J3, then linearly interpolating (as per method in footnote 25), produces the same results as the bottom row of Table J5 (the average discrepancy between the simple ratio method and the individual regression method, across the delay bands, is just under 0.1%).

Annex K
Strategic output elasticity of cost

Objective. The strategic cost of delay is estimated through the cost of adding buffer to schedule. The specific question addressed in this annex is to what extent a given change in a unit of output is associated with an equivalent change in cost. For example, if an airline increases its block hours from one year to the next by 10%, does this incur a 10% increase in crew costs, or is the change in cost proportionally more, or less? This may be examined through the output elasticity of cost.

Definitions. The output elasticity of cost, i.e. the elasticity (responsiveness) of cost with respect to output, is defined as:

$$\varepsilon_C = \frac{\Delta C / C_i}{\Delta Y / Y_i}$$

ΔC is the change in cost, C_i the initial cost, ΔY the corresponding change in output and Y_i the initial output. Possible values of ε_C are summarised in Table K1.

Table K1. Cost elasticity values and interpretation

Cost elasticity	Type of elasticity	As output increases, cost changes …	Direction of changes
$\varepsilon_C > 1$	elastic	… proportionally more	same
$\varepsilon_C = 1$	elastic (unity)	… in proportion	same
$0 < \varepsilon_C < 1$	inelastic	… proportionally less	same
$\varepsilon_C = 0$	inelastic (perfect)	… cost does not change	n/a
$0 > \varepsilon_C > -1$	inelastic	… proportionally less	opposite
$\varepsilon_C = -1$	elastic (unity)	… in proportion	opposite
$\varepsilon_C < -1$	elastic	… proportionally more	opposite

Simplifying, $|\varepsilon_C| > 1$ describes an elastic relationship (the cost changes proportionally more than the output) and $|\varepsilon_C| < 1$ describes an inelastic relationship (the cost changes proportionally less than the output). Note that an elastic change with $\varepsilon_C > 1$ could result from a simultaneous increase in cost and output, or, a simultaneous decrease.

Overview. Output elasticity of cost is used to explore economies of scale (notably in the network contexts of rail, freight distribution and telecommunications). The simplest approach to the strategic costs of adding buffer to schedule is to treat them as being (positive) unity elastic, whereby the rates of change of cost and output are equal. For example, a 10% increase in block hours is associated with a 10% increase in crew costs: with no economy, or diseconomy, of scale.

Technical note. Researchers often model the responsiveness of one variable (e.g. demand) to a change in another variable (e.g. price), in order to establish a causal model, which can be used to predict future change. Commonly, *price elasticities of demand* are evaluated, which are almost always negative. For this reason, the sign of the elasticity is often ignored. In this annex signed elasticities are needed to specify the relative directions of change: for example, sometimes airline costs decrease during a period when an output increases (as discussed below). A crude approach is taken in this annex to explore high-level changes between costs and output. In elasticity measurements, it is important to appreciate the implications of choosing the right type of output (e.g. tonne-kilometres *versus* kilometres). In each case here, block hours are used, respecting the generic time-based nature of these calculations. Crew, fleet and maintenance costs are examined independently; a more comprehensive analysis in future could employ a joint regression model (log-log).

General methodology. The same European ICAO data as introduced in Section 2 were used to explore these elasticities (freighter-only airlines excluded, coverage from 2002 to 2008). Elasticities are normally considered with respect to relatively small changes, hence we have chosen year-on-year changes within airlines, rather than over a longer period of time. Each year-on-year, 'before' and 'after' pair (e.g. 2002 and 2003), for which data were submitted, was treated as a separate observation, n. The results are thus biased towards airlines with fewer annual omissions. Data were submitted to ICAO in USD and corrected to EUR using the exchange rates in Annex E. To reduce inflationary effects, the cost in the 'after' year of each pair was adjusted back to the 'before'-year Euros, using the inflation rates in Annex E.

Data cleaning. For each cost type examined (crew, fleet, maintenance) the largest 5% of elasticities (absolute) were removed from the analysis as outliers (practically all of these were produced by very small changes in reported block hours).

Discussion. The output elasticity of cost expresses (here) how costs change in relation to changes in block hours. From the crude use of the ICAO data outlined above, it is not possible to establish to what extent these changes in block hours were *caused* by addition of buffer, nor the extent to which the contemporaneous changes in costs were *caused* by the change in block hours. However, whether a 10% change in block hours in the data is caused by the addition of buffer, or some other factor, is not fundamental. Such a change in block hours could be imposed by a change in airport slots or by some other scheduling constraint, for example.

Indeed, addition of buffer on one leg may impose undesirable rescheduling changes on other legs - both types of change contributing to additional block hours. Conversely, buffer could be imposed by schedule slack, albeit still typically with an associated opportunity cost. Accurate causal attribution of changes in output, in the complex network context, is difficult. Estimations are here based on changes at the aggregate level.

Some of the changes in *costs* will be driven by exogenous factors, rather than by the contemporaneous change in output itself (such as wider market trends, crew pay settlements, shifts to outsourcing maintenance, etc). In some cases, there may be an increase in output over a period when the cost decreases, or an increase in cost during a period of reduced output. Although these changes may be causally linked with adding buffer to schedule in some cases, they are not included in these elasticity estimations. The estimations will be based on the set of observations whereby an increase in output is associated with an increase in cost. Therefore, at least some *known* exogenous factors (such as the market trends in fleet and maintenance costs, discussed in Section 2), not caused by adding buffer to schedule, are prevented from biasing the estimations.

The elasticity estimations will still include cases where block hours are output at a proportionally higher or lower cost, due to (dis)economies of scale. The calculations implicitly assume that most of the ICAO reported costs for a given output are indeed strategic costs, and not tactical costs, which seems reasonable. A bias which has not been corrected is that airlines contributing the highest block hours are those engaged in long-haul, which has different cost characteristics.

When extra buffer is added to the schedule, there may be cases whereby this can be accommodated by efficiency improvements in the network, with an inelastic change in cost ($\varepsilon_C < 1$). Examples might be: (i) particularly small increases in block hours; (ii) increases in block hours made in larger networks. It might be expected that changes under these types of condition could allow the airline to 'sweat' its assets, either because the change is so small, that it is easily accommodated by the network, as in (i), or because the network is so large, (ii). Of the three cost types explored here, perhaps the greatest flexibility arises with crew rostering (although fleet management and powerplant swapping are other important examples of efficiency measures). Full-service carriers often have greater reserve crew capacity than low-cost carriers. We will examine cost elasticities for all three cost types, starting with crew.

Results. Taking crew costs in the ICAO data as the cost, C, Figure K1 is a plot of $\Delta C/C_i$ *versus* $\Delta Y/Y_i$. After the removal of the 5% outliers, it is worth remarking that a credible range of elasticities was obtained. Of the n = 127 remaining observations, 114 were in the range $-10 < \varepsilon_C < 10$ (the full range was -35 to 25). Simple linear regression (solid line) in Figure K1 initially suggests a lack of overall relationship between $\Delta C/C_i$ and $\Delta Y/Y_i$ ($r^2 \approx 0$, sample coefficient of determination). The dotted line ($\varepsilon_C = 1$) separates the inelastic and elastic regions of the main quadrant of the plot. Table K2 is a cross-tabulation of $\Delta C/C_i$ by $\Delta Y/Y_i$.

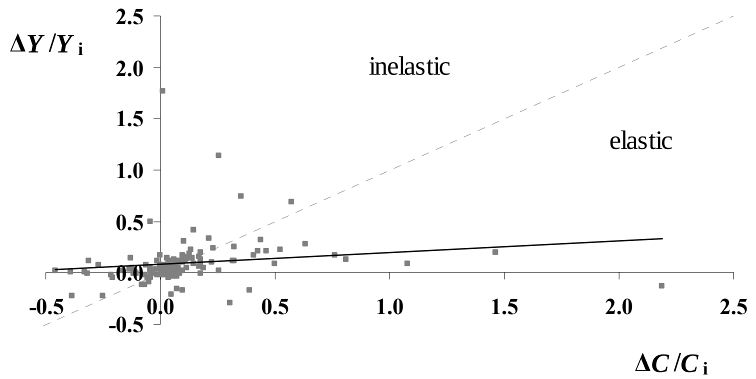

Figure K1. Crew cost changes by block-hour changes

The combination of decreasing block hours and decreasing costs (n = 17, $0 < \varepsilon_C < 25$) is not of primary interest. The increase in block hours associated with a decrease in cost (n = 19, $-35 < \varepsilon_C < 0$) may reflect airlines achieving new economies of scale following a network re-structuring. For the year-on-year pairs in 2002 - 2008, British Airways achieved this three times (the only airline to do so, although in non-consecutive pairs and with a very weak effect for the second of the three periods), two airlines achieved this twice, the rest were single events.

Table K2. Crew cost changes by block-hour changes

Block hours	Cost increase	Cost decrease
Increase	73	19
Decrease	18	17

The decrease in block hours associated with an *increase* in cost (n = 18, $-27 < \varepsilon_C < 0$) was mostly associated with single events per airline, during the 2002 - 2008 period, although British Midland had such an inelastic change for three consecutive financial years following the launch of the low-cost subsidiary bmibaby in 2002 (2003-4, 2004-5, 2005-6; ε_C = -0.23, -0.56, -0.35). In general, these typically single events may reflect diseconomies of scale with output reduction.

These three types of change are logical but not the most common. The prevalent change is also the one of direct interest, whereby an increase in block hours is associated with an increase in cost. These 73 cases were evenly split between inelastic ($\varepsilon_C < 1$, n = 36) and elastic ($\varepsilon_C > 1$, n = 37). There is no marked temporal trend in the median elasticity amongst these 73 observations from 2002 to 2008, although it was lowest in the period 2007 - 2008.

Taking example (ii) from the discussion section, does starting from higher block hours afford better economies of scale? For the 73 cases of cost increase with output increase, a lack of correlation ($r^2 = 0.04$, $p = 0.11$, Pearson) is observed between $\Delta C/C_i$ and Y_i, suggesting no such commonplace economy of scale. Nor was there any clear evidence that a particular type of airline operation (e.g. low-cost or full-service) was more likely to achieve an inelastic increase in block hours, or that a low initial cost per hour would predispose towards this[†]. (It might still be true that low-cost carriers are less able to achieve further economies of scale, due to utilisation already being high, but that these effects were masked by other characteristics of the data).

Analogous calculations were carried out on the ICAO data for the fleet costs (cross-tabulated in Table K3, n = 129) and maintenance costs (Table K4, n = 129). The high incidences of cost decreases contemporaneous with increases in output are consistent with the wider market trend discussions of Section 2.4 (fleet) and Section 2.3 (maintenance).

Table K3. Fleet cost changes by block-hour changes

Block hours	Cost increase	Cost decrease
Increase	46	49
Decrease	9	25

Table K4. Maintenance cost changes by block-hour changes

Block hours	Cost increase	Cost decrease
Increase	55	40
Decrease	18	16

The earlier question of whether a disproportionally small increase in cost might be associated with a particularly small increase in block hours can now be addressed for all three cost types. For crew costs, selecting cases with a positive change in cost and the smallest positive changes in block hours ($\Delta Y/Y_i < 0.05$, n = 17), there was no significant relationship (p = 0.29, Spearman correlation) between $\Delta C/C_i$ and $\Delta Y/Y_i$. There was a significant difference (Mann-Whitney U, p = 0.01) between the median elasticities of the group with the smallest positive changes in block hours and the group with the larger changes ($\Delta Y/Y_i > 0.05$), although, perhaps contrary to expectation, it was the latter group only that had an *inelastic* median elasticity. This might suggest that the smallest increases in block hours, of up to 5% ($0 < \Delta Y/Y_i < 0.05$, averaging at just under 38 hours per day, per network) were made to cost-efficient networks, thus tipping these (elastically) into a diseconomy of scale. These results were remarkably consistent with those of the fleet and maintenance costs[‡], as summarised in Table K5.

Table K5. Significance of relationships for cases of cost increase with output increase

Elasticity property	Crew	Fleet	Maintenance
$\rho_{\Delta C/C_i, \Delta Y/Y_i : \Delta Y/Y_i < 0.05}$	p > 0.10	p > 0.10	p > 0.10
$H_0 : \tilde{\varepsilon}_C(\Delta Y/Y_i < 0.05) = \tilde{\varepsilon}_C(\Delta Y/Y_i > 0.05)$	p = 0.01	p = 0.00	p = 0.03

p values are two-tailed

This evidence suggests that the smallest changes in block hours are neither associated with the smallest proportional changes in costs, nor more likely to be inelastic.

[†] Comparing median elasticities for: (i) upper quartile of cost per hour with rest of group; (ii) lower quartile with rest of group; (iii) upper and lower quartiles. All resulted in non-significant differences (Mann-Whitney U, p > 0.10). Ordinal measurements, such as medians, are used because the values in each category tended to be skewed by a small number of higher values, such that the median is a better representation of the range than the mean.

[‡] Again, for fleet costs, only the group $\Delta Y/Y_i > 0.05$ had an inelastic median elasticity. For maintenance costs, this group had much the smaller median, although it was just elastic (1.1).

In Table K6, elasticity data are summarised from tables K2 - K4, for output increases associated with cost increases.

Table K6. Summary of elasticities for cases of cost increase with output increase

Elasticity property	Crew	Fleet	Maintenance
Cases (n)	73	46	55
Maximum elasticity	13	53	20
Ratio inelastic:elastic	0.5 : 0.5	0.5 : 0.5	0.4 : 0.6
Inelastic median ($\tilde{\varepsilon}_C : \varepsilon_C < 1$)	0.50	0.43	0.46
Elastic median ($\tilde{\varepsilon}_C : \varepsilon_C > 1$)	2.4	2.3	1.9
Overall median	1.0	0.97	1.2

Elasticity values to 2 sf

Conclusion. A fairly crude approach to assessing the strategic cost of adding buffer to schedule has been explored. Further research may point to different conclusions. In Section 2 (main report text), 'initial' unit costs are first derived for low, base and high scenario cases, for each cost type examined (crew, fleet, maintenance). The 'initial' unit costs refer to values before any elasticity correction is made.

For the base scenario costs, there is no balance of evidence in this annex that the initial values should be increased, or decreased, to take account of cost elasticities: Table K6 summarises that as many cost elasticities are elastic as are inelastic, with the three overall medians very close to unity. The initial base scenario values are thus not adjusted.

Table K6 also shows that a number of inelastic cost elasticities centre around 0.5, and a number of elastic values around 2.0. The initial unit costs derived in Section 2 already include previous periods of inelastic, and elastic, changes. There is no evidence that lower or higher starting costs per hour predispose an airline towards greater or smaller elasticities.

Compared with 0.5 of the base values, the initial low scenario values were: already lower for all aircraft (fleet costs); most aircraft within a few percent (maintenance costs); or, somewhat higher (crew costs: on average 19% more, but for most aircraft the exceedance was less than this). The initial low scenario values are therefore not adjusted.

Compared with 2.0 times the base scenario values, all the initial high scenario values were lower. Fleet costs were around 30% lower. Maintenance costs averaged around 35% lower. Crew costs were around 25% lower for narrowbodies, 10% lower for widebodies. These initial unit costs do not thus appear to encompass the full potential cost penalties of increasing output.

For all of the high scenario values, the initial values are increased by half of these shortfalls (as flat rates, rather than aircraft-specific). These fairly modest increases are intended to better reflect the higher costs imposed by diseconomies of scale. This allows for airline acquisition of additional resources, to incorporate buffer into schedule, in unfavourable conditions such as shorter lead times and/or step changes in certain operational costs.

Summary. The strategic cost of delay is estimated through the cost of adding buffer to schedule. The elasticity of cost with respect to output, based on ICAO data, has been considered in this context. For year-on-year observations, crew, fleet and maintenance costs have been compared with changes in block hours. The initial unit costs derived in Section 2 for the low and base scenarios are not adjusted as a result of the elasticity effects. The initial values for the high cost scenarios are, however, moderately increased to reflect potential diseconomies of scale.