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Aviation in a sustainable world

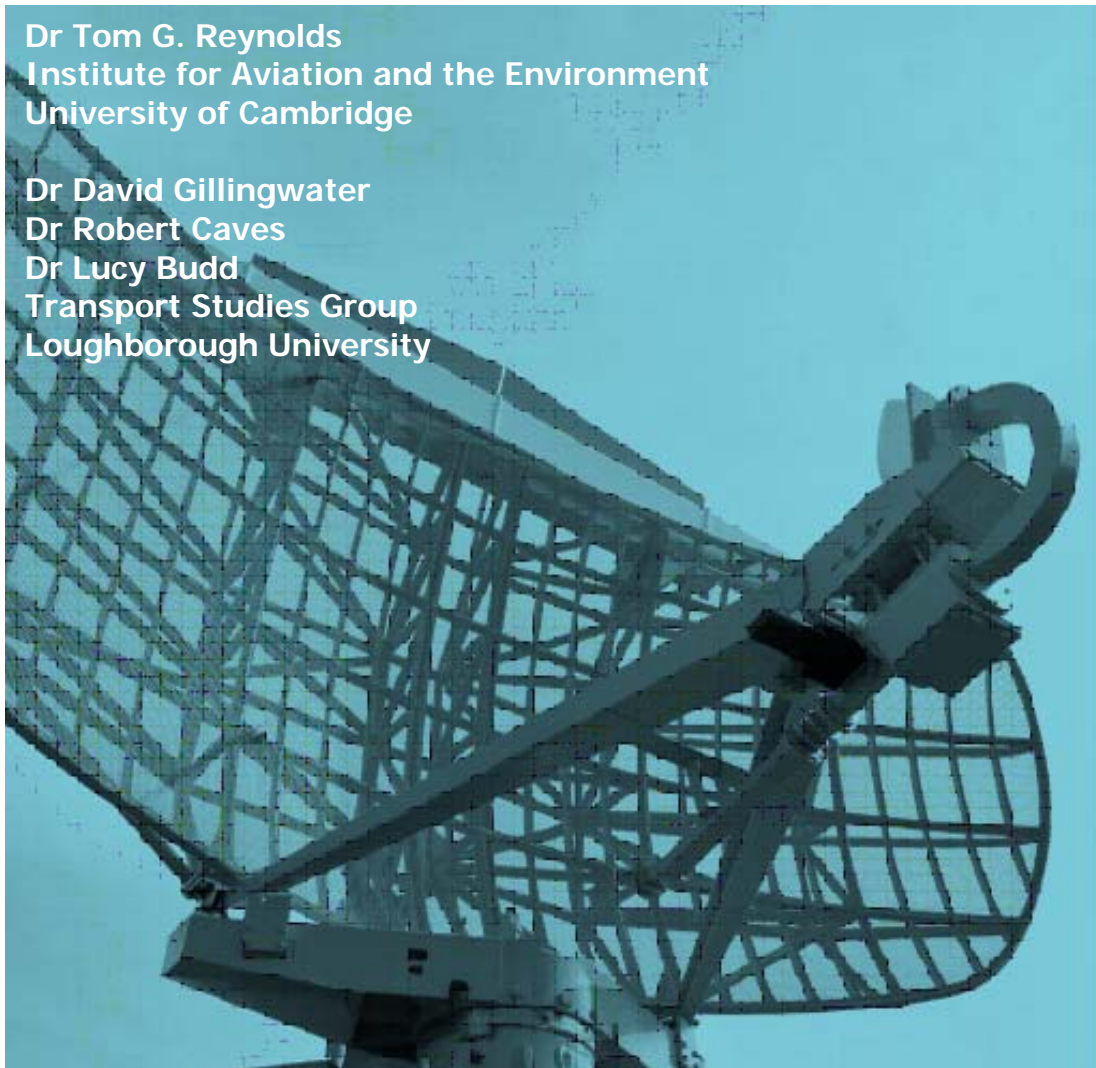
Omega

Climate Related Air Traffic Management Final Report

Assessing the role of air traffic management in reducing
environmental impacts of aviation

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About Omega

Omega is a one-stop-shop providing impartial world-class academic expertise on the environmental issues facing aviation to the wider aviation sector, Government, NGOs and society as a whole. Its aim is independent knowledge transfer work and innovative solutions for a greener aviation future. Omega's areas of expertise include climate change, local air quality, noise, aircraft systems, aircraft operations, alternative fuels, demand and mitigation policies. Omega draws together world-class research from nine major UK universities. It is led by Manchester Metropolitan University with Cambridge and Cranfield. Other partners are Leeds, Loughborough, Oxford, Reading, Sheffield and Southampton.

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Further details can be found at: www.omega.mmu.ac.uk

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Executive Summary

Motivation

Making the Air Traffic Management (ATM) system more efficient is one of the primary areas of interest for reducing the environmental impact of aviation. In an ideal air transportation system, all aircraft would fly their optimal four-dimensional trajectories between airports, comprising the most direct route (accounting for wind), at their most fuel-efficient altitude and speed. This would lead to lowest fuel burn and carbon dioxide emissions, as well as reducing many other environmental impacts (such as noise and air quality) if designed appropriately. However, the practicalities of the ATM function with its primary objectives of keeping aircraft safely separated often introduces constraints which lead to aircraft flying less efficient trajectories and hence at greater environmental impact than the ideal. Hence improvements to the ATM system which allow more efficient flight profiles at equivalent or improved levels of safety offer the potential for better environmental performance. Although aircraft and engine technological enhancements offer great environmental promise in the longer term, they will take many years of development and fleet turnover before they even begin to impact the operational system with sufficient numbers to have a measurable environmental benefit. In contrast, modifications to the ATM system can be implemented (in theory) in shorter timescales and have immediate and widespread affect over *all* the aircraft being managed.

This Omega study was initiated to explore the fundamental issues surrounding the role of ATM on the environmental performance of the air transportation system as a whole, now and into the future. The concept of flight inefficiency was used for this purpose to quantify how far the actual behaviours of aircraft in the current ATM system were from their optimal behaviours. The key questions for the study were developed after extensive consultation with stakeholders and can be summarised as:

1. What are the current inefficiencies and their causes in ATM?
2. What are the environmental impacts of these inefficiencies?
3. What are the priorities for future ATM system design to achieve environmental impact reduction?
4. Which inefficiencies cannot be removed?
5. What are the barriers for change and how can these be overcome?
6. What is the role of airport capacity?

The work focussed on the European region in order to provide focus to the study, but comparisons with and discussions of other world regions are provided when appropriate.

Key Findings

The key findings to each of the study questions are outlined below.

1. What are the current inefficiencies and their causes in ATM?

The inefficiencies in the ATM system have different potential causes in the different flight phases. During taxi-out operations, inefficiencies may take the form of long taxi routes with higher fuel burn than an ideal, short, unconstrained route. On take off, inefficiencies can be introduced by non-ideal thrust levels, as well as departure procedures that might require aircraft to fly specific paths and profiles for noise abatement and/or traffic separation purposes. Aircraft may also have to leave the origin airport terminal area over specific departure fixes which link with appropriate downstream air routes but which may require a longer flight path and/or non-optimal climb profiles within the terminal area compared to a more direct route. In the en route airspace, standard (and often sub-optimal) air routes and flight levels are typically used to help manage traffic and aircraft often fly around regions of restricted or congested airspace, as well as adverse weather. Avoiding regions of expensive airspace may also be a factor in some regions. On approach to the destination airport, aircraft typically enter the terminal area via an arrival fix which may also require non-optimal descent trajectories. If there is airport congestion, aircraft may need to enter holding patterns or be vectored for separation purposes. Finally, the lateral and vertical elements of the arrival procedure will likely be constrained by the need to space, merge and sequence traffic for landing which may force them away from their optimal approach procedure. Finally, long taxi-in routes may be required after landing.

Two types of analysis were conducted to quantify the overall inefficiency levels as well as the relative importance of each of these factors in European ATM, involving (i) a simple *lateral ground track extension metric*, and (ii) a more complicated but comprehensive *extra fuel burn metric*. The track extension analysis identified that, on average, aircraft fly approximately 16% (57 nm) longer track distances in Europe compared to the minimum great circle track distance. Of this total ground track extension (TGTE), around 16% (9 nm) is in the departure terminal area (i.e. within 50 nm of the departure airport) and this can be almost entirely attributable to standard departure procedures. Approximately 37% (21 nm) of the TGTE occurs in the en route phase of flight due to standard routes and restricted airspace, congestion and adverse weather. The remaining 47% (27 nm) of the TGTE was attributable to the arrival terminal area, over half of which was found to be due to the need to put aircraft into holding stacks (to absorb delay and maximise runway throughput) and vector them for final approach, while the remainder was due to standard arrival procedures. Despite the added complexity due to the requirement to model optimal aircraft fuel burn by flight phase, the equivalent fuel-based analysis highlighted a number of key insights which were not possible with the simpler lateral track extension analysis. The analysis of an average European route indicated that the extra fuel burn was, on average, 30% above the theoretical minimum fuel burn, i.e. nearly twice the ground track extension inefficiency. Fuel-based analysis permits the inclusion of vertical, speed and aircraft taxi elements into the analysis, and these were found to account for nearly a quarter of the extra fuel burnt, none of which

can be captured when only considering ground track extension from radar data. In addition, the split of extra fuel burn by flight phase was observed to be very different than the equivalent track extension breakdown, with the departure terminal area taking on a much more prominent role than in the lateral analysis due to the high fuel burn rates in the take-off and climb phases that are predominantly occurring in this flight region.

2. What are the environmental impacts of these inefficiencies?

Although a more thorough analysis is required (and on-going), the fuel-based analysis of the average European route has indicated that aircraft may burn considerably more total fuel, and hence have higher CO₂ emissions than assumed in some key environmental impact prediction studies. For example, the often-cited Intergovernmental Panel on Climate Change (IPCC) studies into environmental impacts of aviation assume fuel-based inefficiencies of 15% (and dropping to 5% in 2015) to account for sub-optimal trajectories introduced through ATM practices. The effects on pollutants such as NO_x are more difficult to quantify because they depend not only on the amount of fuel burnt, but also the engine settings and atmospheric conditions at the time of the extra fuel burn, and this needs to be studied more carefully too.

The fuel-based analysis also indicated that the extra fuel burn is not evenly spread among the different flight phases. A disproportionate amount of extra fuel burn (compared to extra distance flown) occurs in the terminal areas and hence at lower altitudes. Although this does not affect the environmental impacts of the CO₂ due to its very long lifetime (and hence, over time, it becomes mixed over a global scale), it does affect the climate change and local air quality impacts of some other pollutants, such as NO_x.

The constraints of aircraft trajectories that cause the flight inefficiencies can affect the ability to accommodate “best practise” operational techniques that ATM always try to accommodate to minimise noise, local air quality and fuel burn/climate change effects.

3. What are the priorities for future ATM system design to achieve environmental impact reduction?

The findings from this study give important pointers towards appropriate priorities for future ATM designs to reduce flight inefficiency and hence environmental impacts of aviation. By examining the inefficiencies in each phase of a typical flight, it is possible to identify future operational concepts for improved environmental performance, and hence the supporting technologies and procedures necessary to enable these changes to be made. These include:

- At the start of a flight, optimising the push-back time and sequence, then optimal taxi routing with no holding, both enabled

through the use of advanced algorithms and datalink communications.

- On take-off, use of engine power optimisation, followed by departure procedures designed to allow maximum use of optimal initial climb profiles to minimise noise and air quality effects.
- In departure, cruise and descent phases, use of optimised lateral, vertical and speed profiles that reduce fuel burn tailored to each aircraft coupled with strategic de-confliction tools enabled by 4D trajectory management technologies and advanced Communication, Navigation and Surveillance technologies.
- On approach, increased use of optimal approach profiles to minimise fuel burn and possibly changed procedures such as steeper approaches to improve noise performance.
- On landing, “smart” runway and gate allocation to minimise taxi time, distance and emissions, again enabled through the use of advanced algorithms and datalink communications.

4. Which inefficiencies cannot be removed?

ATM evolution alone cannot eliminate all of the inefficiencies identified, i.e. some “residual inefficiencies” would remain due to fundamental constraints. These include the need to keep aircraft safely separated from each other, as well as adverse weather and terrain. However, advanced technologies and procedures may allow separation minima to be safely reduced, but never eliminated entirely. These residual effects are likely to take on increasing importance in the future due to continued growth in traffic demand, and hence growing congestion. The relationship between flight inefficiency and congestion is a key one requiring future work.

The requirement to accommodate the needs of multiple users of airspace (e.g. commercial, general aviation, military, etc.) means that there will always be some restrictions on the airspace available to commercial aviation. Wholesale removal of restricted airspace is unrealistic and hence this is another source of residual inefficiency, but minimising the extent and/or times of use of these restricted regions would help the environmental performance of the commercial ATM system.

The need to consider multiple, and sometimes competing, environmental issues at once could also be considered a type of residual inefficiency. For example, departure and arrival procedures that involve longer routes (and hence greater fuel burn and climate change effects) to minimise noise effects will appear as sub-optimal in terms of one environmental impact, but may be the best compromise option.

Other stakeholders play an important role in determining allocation of airspace to different users and nationalities, determination of procedures and resulting separation requirements, creation or restriction of airport capacity,

and how ATM should prioritise different environmental impacts when trade-offs exist. Therefore, not all the inefficiencies that manifest in this analysis can be attributed entirely to ATM and this needs to be accounted for when determining what benefits may be accrued from ATM system evolution. The interface with and the roles of the other stakeholders need to evolve also if maximum environmental performance is to be achieved in the future, as described next.

5. What are the barriers for change and how can these be overcome?

Apart from the residual inefficiencies identified in the preceding section, there are other barriers to progress towards an optimum ATM system. Many of the ATM improvement options rely on advanced technology development, the pace of which is uncertain. Similarly, development of procedures which take full advantage of the new technologies often take a considerable amount of time. Indeed, the pace of procedural development in the past has lagged the technological capabilities within the system by a significant period. Effective integration of new technologies in the future will require a collaborative effort involving all stakeholders. Incentivising the necessary change is another major institutional barrier if system performance is to be improved in the face of growing demand in the future. Other barriers to change include political will to harmonise airspace (as in SESAR or to eliminate airspace charging differentials) and the requirements of other airspace users such as military and general aviation. Controller and pilot workload also have fundamental limits which affect future system design: the impacts of modified technologies and procedures on these groups need to be carefully considered in light of these limits. Finally, arrival holding/vectoring was identified as a major issue in both the lateral and fuel-based analyses. Limited airport capacity causing arrival delay is the root cause of this issue, while increasing airport capacity is one of the most contentious and time-consuming aspects of future air transportation system evolution.

6. What is the role of airport capacity?

Planned increases in airport capacity are unlikely to keep pace with growth in aircraft movements, and hence it will become increasingly important to manage arrival delay in a more environmentally-friendly way. The importance of airport capacity to inefficiency levels within Europe have also been examined in this study. A harmonised assessment of current European airport capacities has been used with projections of aviation demand to estimate European airport capacity needs in the future. Across the top 30 airports, the average requirement was for a 1.68 times increase in capacity in 2050 compared to 2005 levels just to maintain current levels of arrival delay. Adding airport capacity is difficult to accomplish, requiring either new runways at existing airport, new airports, or modified operating practices. Given the long lead times associated with all of these options, congestion is likely to increase in the future at some airport. With the current ATM system in Europe, airport capacity limitations are likely to manifest as significantly

greater inefficiencies in terms of holding/vectoring in the destination terminal area, en route congestion and even ground holding in the arrival terminal area. Only with increased airport capacity and a transition to future ATM systems along the lines discussed above is it likely that the dual challenges of handling increased traffic along with reduced environmental impact per flight will be met.

Conclusions

The conclusions that have emerged from this study can be summarised as:

- ATM has a fundamentally important part to play in reducing the environmental impacts of aviation.
- Flight inefficiency is an effective way of quantifying the current environmental performance of ATM and helping prioritise future evolution strategies.
- All phases of flight need to be considered: those in the terminal areas cannot be neglected due to the important flight inefficiencies in these regions.
- Fuel-based analysis, although more complicated to use, provides significant additional insights on flight inefficiency and resulting environmental impacts compared to the more common lateral-based analysis.
- Not all flight inefficiencies can be attributed to ATM and effective co-operation between stakeholders will be critical to removing these in the future.
- There are some residual inefficiencies that may not be possible to eliminate entirely due to fundamental constraints, such as the need to keep aircraft safely separated.
- Collaboration between stakeholders is of fundamental importance.

Future Needs

This Omega study has only been able to present a relatively broad assessment of the importance of air traffic management on environmental impacts of aviation. There is much additional work that needs to be done in many areas, but the key ones flowing from this report are:

Additional Research Topics

- Need for more extensive flight data analysis comparing the fuel-based and lateral analysis to enhance the insights that can be gained from their use.
- More work is needed to explore the fundamental relationships between safety, capacity, congestion and flight inefficiency.

Increased Collaboration

- Need for agreement on a consistent set of environmental performance metrics and analysis methodologies to harmonise the

on-going efforts in this area within different stakeholder groups (which are currently inconsistent and hence difficult to compare).

- Collaboration could be strengthened between many groups such as:
 - ATM researchers, climate scientists and local air quality modellers so a realistic assessment of the environmental impacts of aviation is to be made.
 - ATM researchers, airlines and air navigation service providers to facilitate access to operational data (with appropriate protections) which would support research work that would be of value to all parties.
 - Air navigation service providers, regulators, other airspace users (e.g. military) and service providers (e.g. weather data). Whilst there are lines of communication at the operational level, it is far from clear that there are connections at the research and analytical levels.
- Having an independent venue for the sharing of knowledge amongst stakeholder groups against an agreed set of metrics, methodologies and data would facilitate these collaborations. Omega provides one option of such a venue.

Added Value & Likely Customers for the Study Outputs

The structure, methods and results from this study expand the current state of the art and hence add value to this increasingly important area of ATM performance quantification that many stakeholders are actively pursuing. Detailed discussions with key stakeholders in the ATM domain have been held throughout this project. Their feedback has been invaluable, while at the same time the Omega investigators have contributed to stakeholder reports and analyses, demonstrating the value of a collaborative activity as enabled through the Omega project.

It is hoped that the study outputs will be of interest to a wide range of customers, from the ATM community, as well stakeholders who use, are affected by or help develop ATM operations, such as airlines, airports, community groups, government, regulatory and policy making bodies.

1.0 Introduction

In an ideal air transportation system, all aircraft would fly their optimal four-dimensional trajectories between airports, comprising the most direct route (accounting for wind), at their most fuel-efficient altitude and speed profiles. This would lead to lowest fuel burn and carbon dioxide emissions, as well as reducing many other environmental impacts (such as noise and air quality) if designed appropriately. However, real world constraints lead to aircraft flying less efficient trajectories and hence at greater environmental impact than this ideal. The practicalities of the Air Traffic Management (ATM) function influence the trajectories that aircraft can fly, and hence improvements to the ATM system offer the potential for better environmental performance of all aircraft being controlled within a given region.

Initiatives to assess the performance of the ATM system are now underway. The concept of flight inefficiency to quantify the difference between actual and ideal behaviour is becoming widely used for this purpose. The increasing attention being given to environmental impacts of ATM is highlighted by the recent trials of “environmentally optimal” trans-Pacific flights as part of the Asia and South Pacific Initiative to Reduce Emissions (Aspire) [Kelly, 2008] (a similar programme is also underway between US and Europe called the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) [Turner, 2008]). In the initial phase, three Aspire trial flights were given full priority over other traffic such that normal ATM constraints (which can lead to delay, extra fuel burn and emissions) were removed as much as possible. This allowed the flights to perform their preferred taxi-out, take-off, climb, cruise, descent, approach, landing and taxi-in procedures to the extent that current technologies and procedures would allow. Fuel burn reductions of 5-6% were observed in these flights compared to the standard flight. Even larger benefits are expected once new technologies associated with next generation ATM systems are introduced. For example, the Intergovernmental Panel on Climate Change (IPCC) suggests that improvements in ATM could help to improve overall fuel efficiency by 6-12% per flight [IPCC, 1999]. Some air navigation service providers are incorporating fuel burn and carbon dioxide reduction as part of their environmental performance targets. For example, in the UK, NATS aims to “reduce by an average of 10% per flight the ATM CO₂ emitted by aircraft while under [their] control by 2020, against a 2006 baseline” [NATS, 2008]. The major ATM modernization initiatives in Europe (Single European Sky ATM Research (SESAR) [Eurocontrol, 2009]) and the US (Next Generation Air Transportation System (NextGen) [JPDO, 2007]) have broader environmental impact reduction objectives encompassing noise, air quality and climate change (rather than specific targets for fuel reduction from ATM), but both identify ATM improvement as a crucial element in meeting their overall goals. The global trade association for air navigation service providers, the Civil Air Navigation Services Organisation (CANSO) has also assessed the current environmental performance of ATM efficiency and set targets for making improvements in the future [CANSO, 2008].

The Omega “Climate Related ATM” study that is the focus of this report was designed to complement these existing efforts within the ATM stakeholder community. An extensive consultation exercise with stakeholders was conducted in the initial stages of the overall Omega activity to identify gaps in current knowledge and establish priorities for the future. In the ATM domain, the key questions identified from this exercise were:

- What are the current inefficiencies and their causes in ATM? (see Section 2)
- What are the environmental impacts of these inefficiencies? (see Section 3)
- What are the priorities for future ATM system design to achieve environmental impact reduction? (see Section 4)
- Which inefficiencies cannot be removed? (see Section 4)
- What are the barriers for change and how can these be overcome? (see Section 4)
- What is the role of airport capacity? (see Section 5)

Responding to these questions was the key objective of this Omega study and each is discussed in the sections indicated in brackets. Section 2 discusses the causes of flight inefficiency, and presents analysis which quantifies the overall system inefficiency levels and a breakdown of its causes within Europe. Section 3 discusses the environmental implications of the inefficiency analysis. Section 4 presents a discussion on the remaining key questions, in terms of how the findings can be used to identify priorities for future ATM system evolutions that reduce flight inefficiency, what inefficiencies it may not be possible to remove, and the major barriers to change. Section 5 presents an assessment of the state of European airport capacity today and capacity levels that may be needed in the future, given this was identified as one of the major barriers to change. A summary of the key findings and future needs is presented in Section 6.

The work focussed on the European region in order to provide focus to the study, but comparisons with and discussions of other world regions are provided when appropriate.

2.0 Flight Inefficiency

2.1 Literature Search

Quantitative assessment of the performance of the ATM system is a relatively new area of research. The IPCC report "Aviation and the Global Atmosphere" [IPCC, 1999] previously mentioned summarised the main studies in existence at that time, from which it concluded that a potential fuel efficiency gain of 6-12% per flight was possible through improvements in global ATM. They further identified an additional 2-6% reduction in fuel burn through operational measures used by individual aircraft, such as "optimizing aircraft speed, reducing additional weight, increasing the load factor, reducing non-essential fuel on board, limiting the use of auxiliary power units, and reducing taxiing". Two of these six additional operational measures can only be implemented with the cooperation of ATM (optimizing speed and reducing taxiing) and hence it is reasonable to interpret the potential inefficiency directly or indirectly attributable to ATM in the IPCC report to be in the 7-14% range.

Since the publication of the IPCC report, and in order to better understand the environmental impacts of ATM, flight inefficiency metrics of different forms have started to be widely used, most of which utilise route extension as the flight inefficiency metric of choice. Since 2002, Eurocontrol have included a flight inefficiency indicator to its annual Performance Review Report [Eurocontrol, 2002]. These track the aggregate performance of the Eurocontrol airspace through a simple track extension metric that measures the actual ground track flown relative to the shortest great circle distance. In the latest version of that report [Eurocontrol, 2008a], they include an ATM performance target calling for a reduction in the annual average track extension of 2km/flight year-on-year, as illustrated in Figure 1. This also highlights some of the inefficiency levels observed in the European ATM system: an average of 48.9 km (26.4 nm) route extension was observed in 2008 in the en route phase, i.e. excluding the terminal areas defined by 30 nm range rings. Inefficiencies within these regions were not reported.

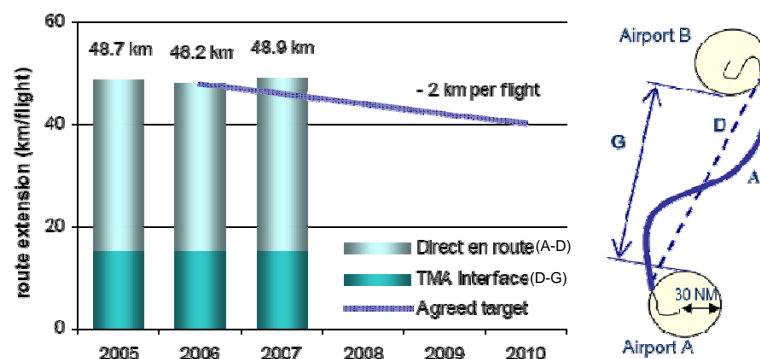


Figure 1: Eurocontrol Route Extension Metric (adapted from [Eurocontrol, 2008a])

An initial assessment of the "benefits pool" to determine the maximum possible benefit if all flights were optimized in the US under a Free Flight

program was conducted in 2003 [Howell et al., 2003]. They discussed the possible causes of flight inefficiency in the en route (i.e. primarily cruise) phase of flight, undertook an analysis of flight data to determine average en route track extension, and converted it to an aggregate cost impact. This work was expanded to include a comparison of track extension data between Europe and the US [Kettunen et al., 2005]. The results suggested that aircraft fly around 10% excess distance in Europe, compared to 6-8% in the US. 70% of the total excess distance flown in the US was found to take place within terminal airspace and the remaining 30% in en route airspace. The European study supported this finding based on the results for a very limited number of airport pairs.

There are very few quantitative studies in the open literature that consider flight inefficiency metrics other than track extension. Eurocontrol have studied vertical inefficiencies [Fuller, et al., 2004] and have discussed the challenges associated with their use in terms of identifying optimum cruise altitudes for a given flight. Their compromise was to use vertical inefficiency metrics in terms of time spent at or above a threshold cruise altitude with the implicit assumption that higher cruise altitudes are superior in terms of efficiency. The report concluded that much more work was required in this area. Vertical inefficiencies were also assessed for the first time in the latest Eurocontrol Performance Review Report [Eurocontrol, 2008a]. They were considered to be an order of magnitude lower in impact than the lateral inefficiency in terms of route extension, but it was unclear to what optimum vertical profile they were comparing the observed vertical profiles. Some of these studies also make attempts at converting their calculated inefficiencies to fuel burn impacts, however there is little detail provided on this critical step so it is difficult to assess the findings on this aspect.

Data for regions other than US and Europe is scarce. A comparison of the track extension inefficiency levels in *intracontinental* US, Europe and Africa, as well as *intercontinental* flights between Europe and the US (i.e. North Atlantic) and between Europe and South East Asia is provided in [Reynolds, 2008]. This study found track extensions were very similar in level and breakdown in the US and European intracontinental regions, while levels were generally similar in Africa but with much less holding. This was considered consistent with the much lower traffic levels in the African region such that even the basic ATM infrastructure that exists over much of that continent could accommodate the low demand levels at inefficiency levels comparable to the US/European regions. However, African airspace would quickly become much more inefficient if traffic levels increased without major infrastructure upgrades. The North Atlantic intercontinental flight analysis showed the extra enroute track distance in the oceanic flights was slightly larger than the US and Europe intracontinental results as a result of the rigid track structure required by the lack of radar coverage in the oceanic region, but it was noted that these tracks are designed to be wind-optimal rather than providing the shortest ground track distance, and hence these results are slightly misleading. The Europe to South East Asia flight track analysis showed that

track extensions in excess of 1000 nm were not uncommon on some routes due to the limited number of standard routes available to international flights between these regions. Although this study provided interesting insights, it was based on a limited amount of data for each region and extensions to the analysis are on-going.

Fuel-based inefficiency levels are not currently available in the open research literature. Fuel-based ATM inefficiency levels in the Pacific and Atlantic oceanic regions are currently under investigation in the Aspire and AIRE programmes respectively. As described in Section 1, initial trial flights from the Aspire programme are suggesting fuel inefficiency levels of 5-6% due to ATM practices in the Pacific flights from the west coast of the US to and from Australasia. Some unpublished studies from AirServices Australia and used in [CANSO, 2008] report fuel based inefficiency levels in that region of 1-2%, but is unclear against what baseline these numbers are reported.

This Omega study takes the findings identified above, and expands upon them to better quantify the inefficiencies in different flight phases and their causes using track extension and fuel-based metrics; explores the insights that can be gained in terms of environmental impact of the inefficiencies; and interprets the analysis in terms of implications for how to improve future ATM environmental performance.

2.2 Causes of Flight Inefficiency

For the purposes of this study, flight inefficiency is defined as anything that causes an aircraft to fly a path different to its fuel-optimum four-dimensional (i.e. latitude/longitude ground track, vertical profile, speed profile) trajectory. Flight inefficiency has different potential causes in the different flight phases, as illustrated in Figure 2 and described in the following sub-sections.

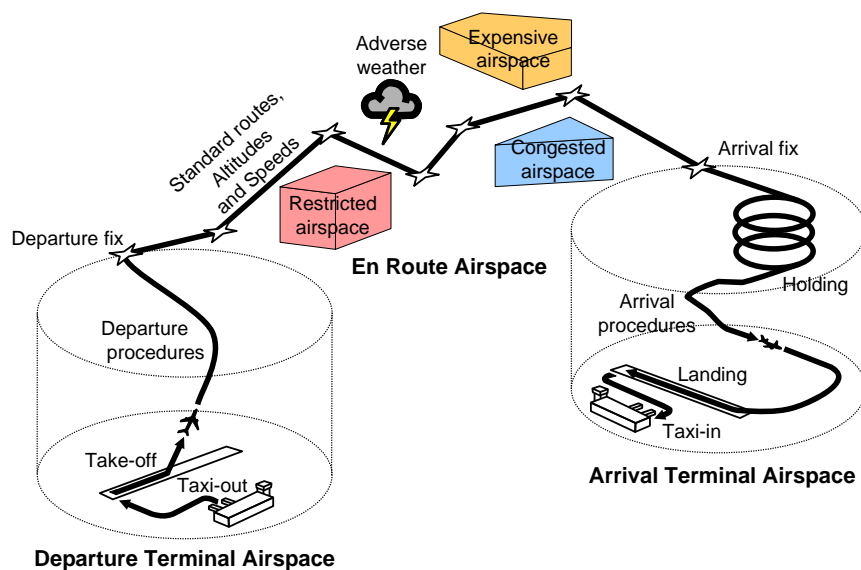


Figure 2: Potential Causes of Flight Inefficiency

2.2.1 Departure Terminal Airspace

Inefficiencies can first affect a flight during taxi-out to the runway (e.g. being given a long taxi route) and the take-off procedure itself (e.g. requiring use of full thrust). After take off, inefficiencies can be introduced by the departure procedures that might require aircraft to fly pre-defined trajectories for noise abatement and/or traffic separation purposes. Aircraft may also have to leave the origin airport terminal area over specific departure fixes which link with appropriate downstream air routes but which may require a longer flight path within the terminal area compared to a more direct route. Example flight tracks into and out of Dallas Fort Worth airport which illustrate the ground track extension introduced by the departure (and arrival, discussed later) procedures are shown in Figure 3.

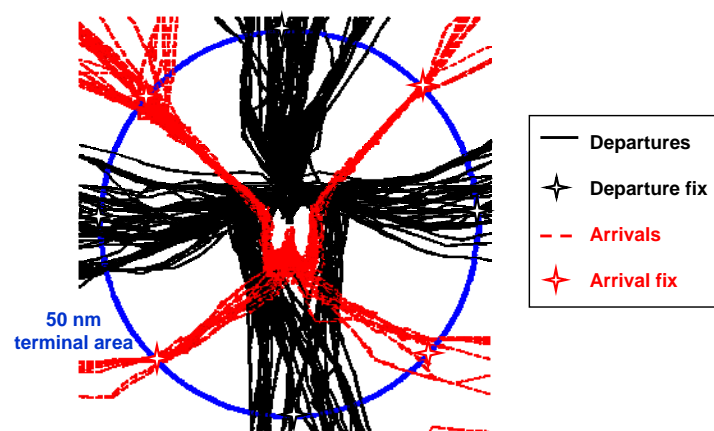


Figure 3: Ground Track Extension due to Standard Departure/Arrival Procedures (ETMS data, from [Reynolds, 2008])

These standard procedures often also impose non-optimal climb profiles and speeds on aircraft which lead to higher fuel burn and emissions during the departure procedure compared to the ideal trajectory.

2.2.2 En Route Airspace

In en route airspace, aircraft often fly standard airway routes with a constrained number of flight levels and cruising speeds available. These constraints are often imposed to manage the complexity of the air traffic control process for the human controllers [Histon & Hansman, 2008]. The standard route network is also designed to accommodate the large number of restricted airspace regions in the world. In addition to these airspace constraints introduced by the basic airspace structure, there are also dynamic constraints due to the need to avoid regions of adverse weather or congested airspace in order to maintain flight safety, comfort or schedule predictability. Some of the impacts of these factors are visible in the ground tracks for all the flights originating from 10 major US airports on one day shown in Figure 4.

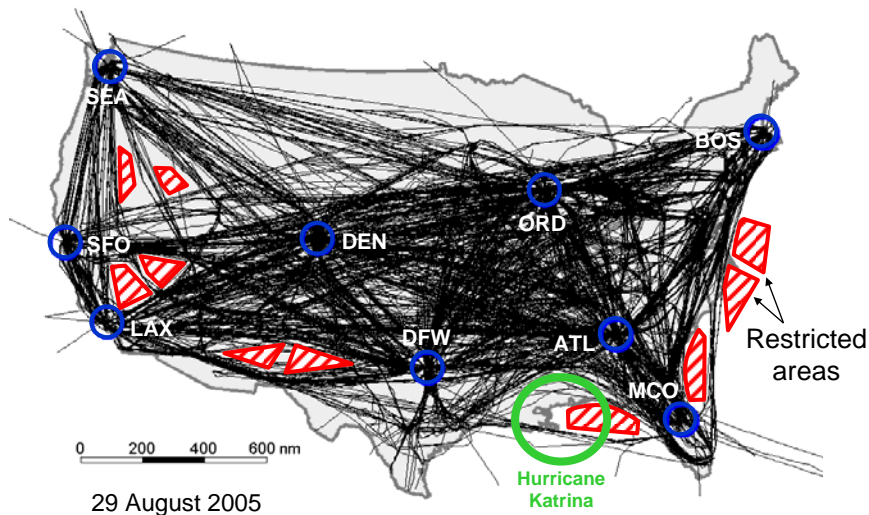


Figure 4: Ground Track Extension due to En Route Airspace Inefficiency (ETMS data, from [Reynolds, 2008])

Standard routes cause the concentration of flights into a limited number of transcontinental flows; restricted airspace causes the avoidance of the hashed regions; and adverse weather causes the avoidance of the circular region in the south-east of the US (this flight data corresponds to the day of impact of Hurricane Katrina).

There is also anecdotal evidence [BBC, 2007] that differences in en route charging regimes in a given area may lead to total cost savings for longer routes (and hence with higher fuel burn and emissions) which go through cheaper charging regions compared to more direct routes that involve more expensive airspace. Europe is the highest traffic region of the world where large differences in airspace charging occur (see Figure 5) and hence this effect could influence flight tracks in this region. The importance of this as an issue to environmental impacts of ATM is discussed in more detail in a companion Omega study report [Gillingwater et al., 2009], but some key findings are discussed in a later section of this report due to their relevance in this study as a potential cause of flight inefficiency.

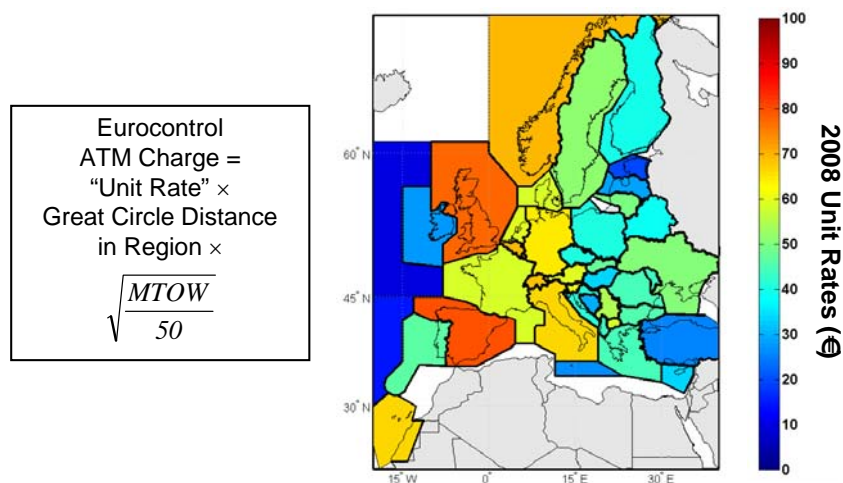


Figure 5: Eurocontrol Airspace Charging Region Differences

2.2.3 Arrival Terminal Airspace

Aircraft typically enter an arrival terminal area via an arrival fix at a specific altitude (or altitude band) and speed which may require a non-optimal descent altitude and/or speed profiles between the top of descent and the arrival fix. Once inside the arrival terminal airspace, if there is airport congestion, aircraft may need to enter holding stacks and/or be vectored for separation purposes. The lateral and vertical elements of the arrival procedure will likely be constrained by the need to space, merge and sequence traffic for landing which may force them away from their optimal approach procedure, in a similar fashion to that described for the departure case and illustrated in Figure 3. Finally, the landing and taxi-in procedures can add inefficiencies, for example by requiring a landing on a runway a long way from the arrival gate necessitating a long taxi route.

2.3 Flight Inefficiency Metrics

A combination of the factors described in the previous section can cause the actual trajectory of any given flight to be inefficient compared to the optimal flight that would have been flown in a completely unconstrained system. The difference between the actual and optimal state behaviour of a flight can be measured in absolute terms (e.g. extra track distance flown in any given phase of flight) or form the basis of an inefficiency metric (IM) with a general form of:

$$\text{Inefficiency Metric (\%)} = IM = \frac{\text{Actual} - \text{Optimal}}{\text{Optimal}} \times 100\% \quad (1)$$

The difference between the actual and optimal state behaviour of a flight can be measured in different flight dimensions, each with their own set of advantages and disadvantages, as presented in Table 1 below.

As illustrated from the literature search, the lateral track extension inefficiency metric based on the difference between the ground track (e.g. from radar surveillance) and great circle distance is commonly used due to its ease of calculation and interpretation, but suffers from a number of disadvantages. The most important for environmental analysis is that a flight with a low lateral inefficiency (e.g. a great circle lateral track is flown) may have relatively poor fuel (and hence environmental) performance due to sub-optimal altitude and speed profiles. Vertical and speed (which can also be considered a surrogate for time) metrics can be defined to complement the lateral metrics, but these similarly suffer from their lack of ability to capture impacts in the other flight dimensions. In addition, they are considerably more difficult to calculate than the lateral case because the optimal altitude and speed profiles depend on the characteristics of each flight which are not readily available with current surveillance systems. Although fuel-based inefficiency metrics (where the actual fuel burn is compared to the optimal

fuel burn) suffer from this challenge as well, they have the distinct advantage of combining the effects in all trajectory dimensions to produce a metric that is directly meaningful for environmental performance assessment, at least in terms of carbon dioxide emissions which are the focus of many ATM environmental performance targets.

Table 1: Sample Inefficiency Parameters

Dimension	Sample "Actual"	Sample "Optimal"	Advantages	Disadvantages
Lateral	Flown ground distance	Minimum ground distance (great circle)	<ul style="list-style-type: none"> • Simple metric • Flown ground distance readily available (radar) <ul style="list-style-type: none"> • Minimum ground distance simple to calculate 	<ul style="list-style-type: none"> • Flown minus minimum ground track not necessarily proportional to environmental impact (e.g. no vertical/speed elements) • Great circle distance is not shortest in presence of wind
	Flown air distance accounting for winds	Minimum air distance accounting for winds	<ul style="list-style-type: none"> • Minimum air distance is better "optimal" measure in presence of wind 	<ul style="list-style-type: none"> • Need accurate wind field information to determine air distance for all flights
Vertical	Average en route altitude	Optimal en route altitude	<ul style="list-style-type: none"> • Captures vertical aspects of inefficiency <ul style="list-style-type: none"> • En route altitude readily available (transponder altitude) 	<ul style="list-style-type: none"> • Does not capture lateral and speed elements • Optimal en route altitude requires info currently not readily available for each flight (e.g. weight, winds)
Speed (or Time)	Average en route speed (or block time)	Optimal en route speed (or block time)	<ul style="list-style-type: none"> • Captures speed (time) aspects of inefficiency • Ground speed readily available (radar) 	<ul style="list-style-type: none"> • Does not capture lateral and vertical elements • Optimal en route speed (block time) requires info currently not readily available for each flight (e.g., weight, winds)
Fuel	Actual block fuel	Optimal block fuel	<ul style="list-style-type: none"> • Proportional to carbon dioxide emissions • Captures lateral, vertical, speed and time aspects 	<ul style="list-style-type: none"> • Actual and Optimal fuel burn requires info not readily available for each flight (e.g., weight, winds)

The sections that follow present inefficiency analyses using the lateral ground track extension and fuel-based metrics in order to illustrate their application and the insights that can be gained which expands upon the current knowledge-base. Flight Data Recorder (FDR) archives from a random sample of Swiss Airlines A320-family flights within Europe during early 2008 was used as the primary data source. This was supplemented with Enhanced Traffic Management System (ETMS) radar track archives for the US system when required.

The latitude and longitude (amongst many other) states were available from both sources with at least 60 second update rates, permitting a detailed lateral flight inefficiency analysis to be conducted (described in Section 2.4)

and mimicking the states that are available in the current radar surveillance environment. The FDR data had the advantage of giving access to aircraft states that are not currently surveilled, but which may be available with future surveillance systems (such as Automatic Dependent Surveillance-Broadcast (ADS-B)) and allow fuel-based inefficiency analysis to be conducted (discussed in Section 2.5).

2.4 European Lateral-Based Inefficiency Analysis

This section summarizes and expands upon the lateral flight inefficiency analysis described in detail in [Reynolds, 2008] where the ground tracks of a large number of flights from the different data sources in different geographic regions were analyzed. Distinctions were made between the departure terminal area, en route and arrival terminal area airspace in order to identify the relative importance of each region, as illustrated in Figure 5. Terminal areas were defined by 50 nm range rings.

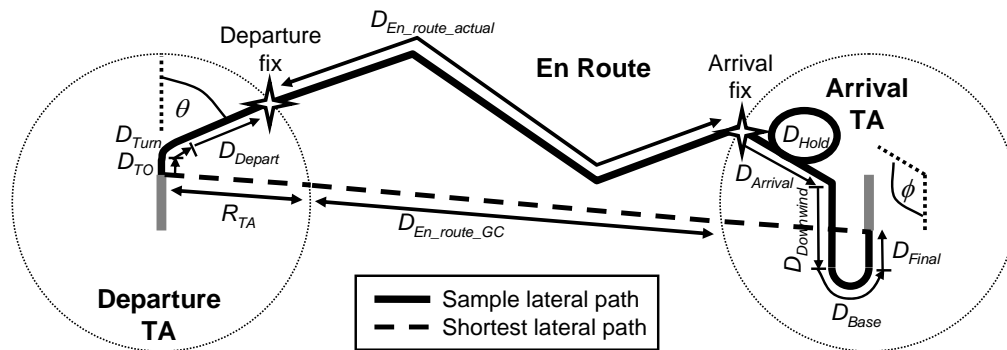


Figure 6: Terminal Area and En Route Ground Track Extension Definitions

Lateral inefficiencies of the form of ground track extension (GTE) flown beyond the great circle (GC) distance in the departure terminal area (DepTA), en route and arrival terminal area (ArrTA) were calculated by:

$$GTE_{DepTA} = (D_{TO} + D_{Turn} + D_{Depart}) - R_{TA} \quad (2)$$

$$GTE_{En_route} = D_{En_route_actual} - D_{En_route_GC} \quad (3)$$

$$GTE_{ArrTA} = (D_{Arrival} + D_{Hold} + D_{Downwind} + D_{Base} + D_{Final}) - R_{TA} \quad (4)$$

$$TGTE = GTE_{DepTA} + GTE_{En_route} + GTE_{ArrTA} \quad (5)$$

The distance components are as defined in Figure 6. The key findings from this analysis for flights within Europe are presented in Figure 7. Part a) shows the ground tracks of the flights that were used in the analysis from the Swiss FDR data. Part b) shows the distribution of extra distance flown in the departure terminal area with an average value of 9.0 nm. A simple model of standard departure procedures presented in [Reynolds, 2008] determined

that, with a random distribution of the terminal area exit angle relative to the runway orientation (denoted as θ in Figure 6), the expected average track extension is 7.6 nm. Hence, the observed track extension can be virtually entirely attributed to this standard departure process of needing to exit the terminal area over a departure fix which does not align with the runway orientation angle.

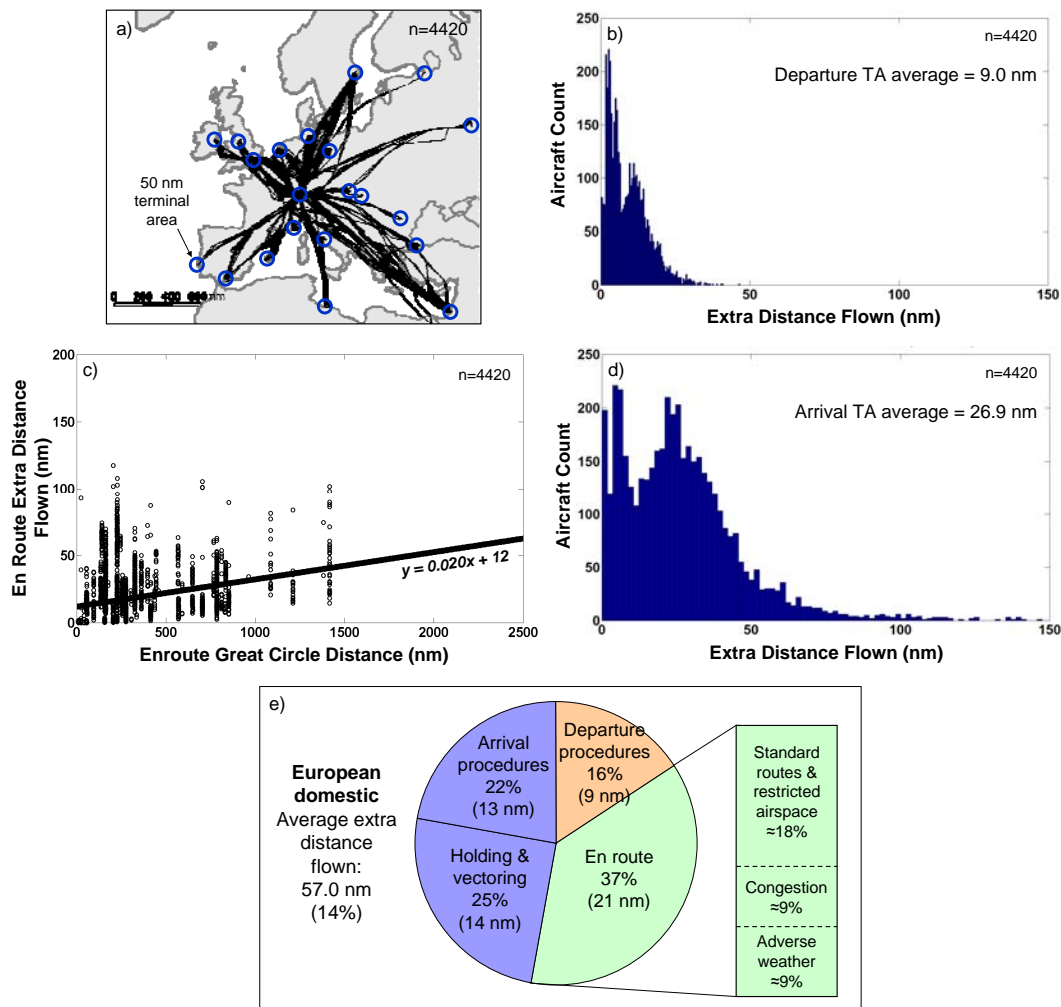


Figure 7: European Lateral Analysis Results;
a) FDR ground tracks; b) Departure TA extra distance; c) En route extra distance;
d) Arrival TA extra distance; e) Extra distance breakdown

Part c) shows the en route track extension as a function of great circle distance. The data contains a great deal of variability, even for a given route (i.e. the data points in a vertical line represent values from a single route in the dataset) as a result of factors such as congestion and weather that affect each flight differently. A best fit line through the data points exhibits a general upward trend with an intercept of 12 nm and a slope of 0.02 nm extra distance for each nm of great circle route distance. The average route length in the FDR dataset was 415 nm: the best fit line to the data equates to an average en route extra distance flown of 21.1 nm for this average route, which relates quite closely to the Eurocontrol published value of 26.4 nm

(48.9 km) for 2007 [Eurocontrol, 2008a]. Their data was based on much more flight data in many more airport pairs than the Omega analysis, but this favourable comparison provides a sanity check.

Part d) shows the arrival terminal area extra distance flown. By contrast to the standard departure procedures, when the standard arrival procedures (coming in over an arrival fix and then aligning with the arrival runway orientation angle) are modelled in a similar way in [Reynolds, 2008] they account for some 13 nm of track extension, i.e. only about half the observed ground track extension in the arrival terminal area. The balance can be attributed to the need to hold and vector traffic to account for arrival delay and to make maximum use of runway resources in these regions. Data that illustrates this phenomenon for arrivals into London Heathrow is presented in Figure 8 below.

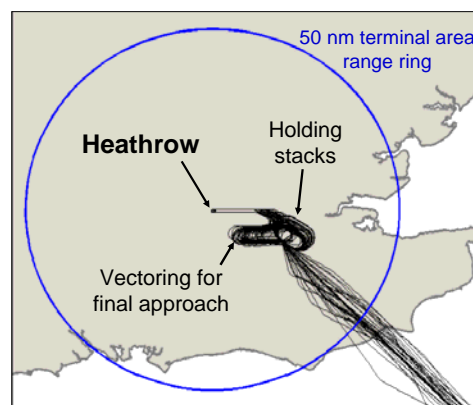


Figure 8: Holding and Vectoring into London Heathrow

Finally, part e) presents the breakdown of lateral inefficiency by flight phase for the average route in the FDR data (i.e. 415 nm). The total ground track extension was found to be 52 nm, equating to a lateral inefficiency of 14%. Of this total, only 16% occurs in the departure terminal area, compared to 37% en route and 47% in the arrival terminal area. The departure terminal area track extension is almost completely due to standard departure procedures, while the arrival terminal area extra track distance is almost evenly split between standard arrival procedures and holding/vectoring. The en route portion of the results can be further allocated to different causes by using data from a similar analysis for the US ATM system. The results of that analysis (reported in full in [Reynolds, 2008]) illustrated the similarities in terms of average lateral inefficiency breakdown characteristics between Europe and the US. The ETMS data used in the US analysis allowed an exploration of the causes of en route ground track extension because it contained data on virtually all commercial flights on specific dates with known traffic levels and presence of adverse weather conditions. By comparing average en route ground track extension during days of relatively high and low traffic conditions, as well as days of high and low adverse weather conditions, it was possible to determine the general impact of these

inefficiency sources. It was found that an extra 10% of system traffic was associated with approximately 10-30 nm extra en route track distance on average. A similar effect was observed when a major adverse weather event, such as the impact of Hurricane Katrina, was analyzed. It is difficult to generalize these results even within the US because the actual impacts are strongly affected by a number of situation-specific variables, such as the location of the congestion or adverse weather events relative to the demand. But the observed impacts give pointers to the relative importance of these causes of inefficiency in current high-density ATM system (e.g. US and Europe): standard routings and restricted airspace accounts for around half of the en route portion of the results, while congestion and adverse weather account for around a quarter each. The uncertainty in the exact allocation between these elements is indicated by the dashed lines in the en route results in part e) of Figure 7.

There are still a few potential causes of flight inefficiency highlighted in Figure 2 that were not considered in the analysis just described: taxiing, expensive airspace and standard altitudes/speeds. The flight data also made it possible to undertake an assessment of the relative importance of the second of these on track extension, i.e. expensive airspace. As mentioned previously, this is most likely to be an issue in European airspace, where differences in ATM en route charges between neighbouring airspace regions can be significant (see Figure 5) and make it possible for the extra cost of fuel on longer routes to be more than offset by lower ATM charges, despite the higher environmental burden associated with increased CO₂ emissions. In order to quantify the relative importance of this issue within Europe, a total of 97 flight plan routes were analyzed from 12 different European airport pairs covering the full geographic extent of the continent. ATM charges on all these routes were determined using Eurocontrol's RSO Distance Tool [Eurocontrol CRCO, 2008], while fuel costs (and CO₂ production) were determined using fuel burn estimates from Eurocontrol's Base of Aircraft Data (BADA) [Eurocontrol BADA, 2004] and average hedged jet fuel prices for 2004 (the year for which the flight plan routes applied) [Gillingwater, 2008]. The routes and CO₂ production as a function of ATM+fuel costs for a B757-200 (a typical aircraft used on European intracontinental routes) are presented in Figure 9.

The dotted line represents the general behaviour expected of a route where the CO₂ production is proportional to the ATM+fuel costs, and hence there is no cost incentive to fly a longer route that has higher emissions. For most of the routes analyzed, this is the case. But two of the routes (highlighted by the dashed oval) do show a slight ATM+fuel cost incentive to fly further (Newcastle/Las Palmas (NCL-LPA) and Madrid/Helsinki (MAD-HEL)). By cross-referencing those routes to the charging areas and rates illustrated in Figure 5, it is seen that this incentive is due to the presence of much lower cost airspace in immediately neighbouring airspace compared to the more direct route. For example, the NCL-LPA route goes into much cheaper oceanic airspace compared to overflying French, Spanish and Portuguese domestic

airspace. This oceanic routing was 123 nm longer and created 3,100 kg more CO₂, but had €837 less ATM+fuel cost (2004 prices), as shown in Figure 10.

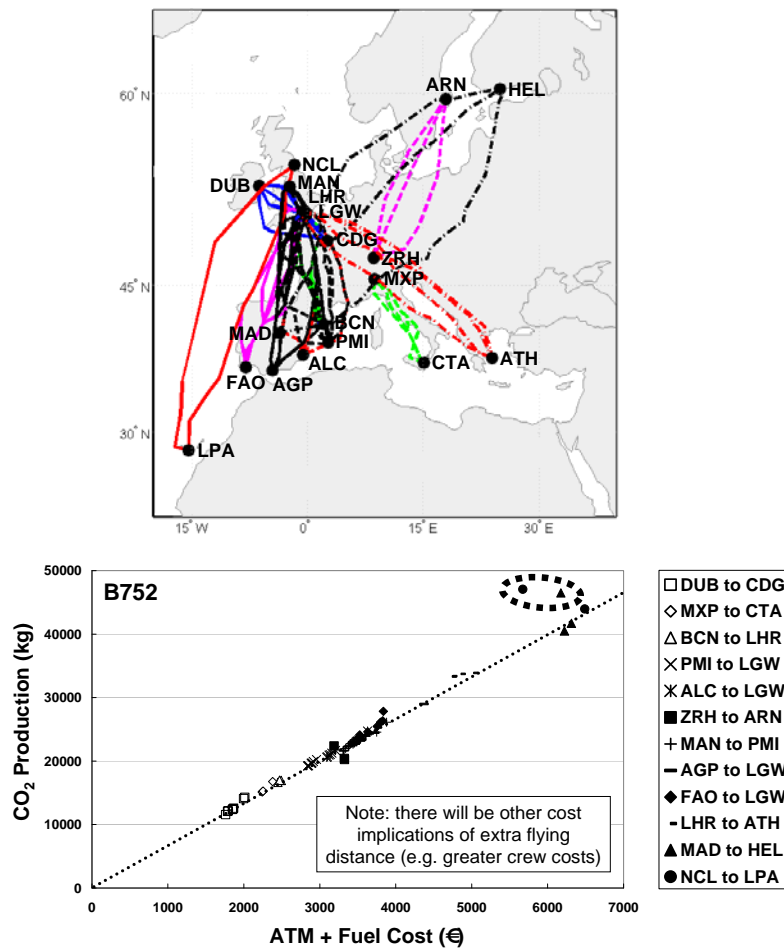


Figure 9: European Airspace Charging Analysis Results

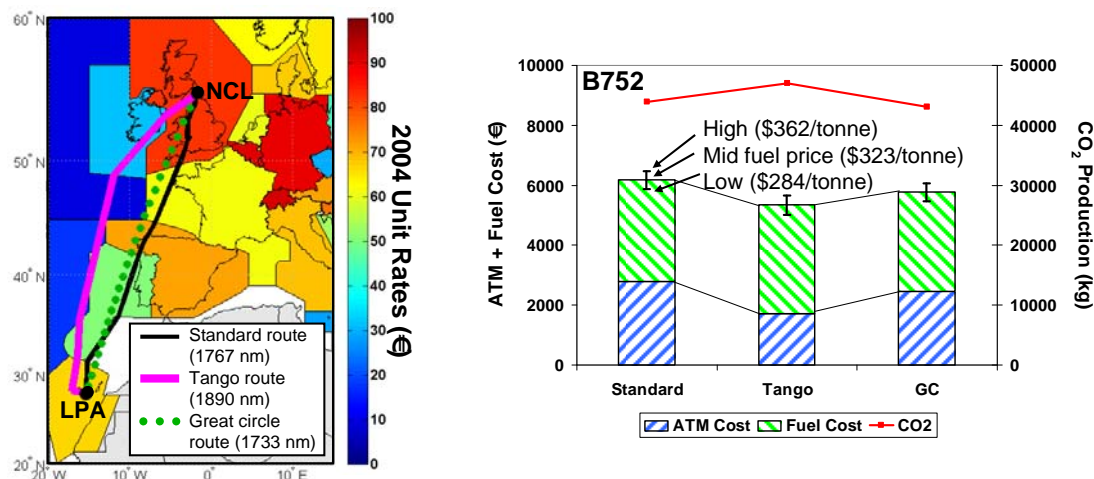


Figure 10: Sample Flight Plans with ATM+Fuel Cost Incentive to Fly Longer Routes

Cost incentives in these types of routes are reduced once other impacts of flying longer routes, such as greater crew costs, are also factored in. Routes where such cost incentives may exist also have low traffic density, so overall

this analysis indicates that expensive airspace is the least important of all the potential inefficiency sources identified in Figure 2 and can be neglected in Europe in all but a few specific cases. The same conclusion is expected to be true for the rest of the world, i.e. there may be a few airport pairs where airspace charging differences may incentivise flying longer routes, but overall the effect is negligible.

This section has highlighted that there are significant insights that can be gained from using the most common (and basic) form of lateral inefficiency metric, i.e. ground track extension. However, it does not provide any way of determining the relative importance of the final two potential causes of flight inefficiency: taxi operations and standard altitude/speeds. The additional insights that can be gained in these regards from using a fuel-based inefficiency metric, along with the added complications this brings, are discussed in the next section.

2.5 European Fuel-Based Inefficiency Analysis

As previously mentioned, fuel-based inefficiency analysis is more compatible with environmental performance assessment, but is also much more complicated than lateral analysis because it requires availability of aircraft states that are currently not routinely surveilled, as well as more detailed modelling of aircraft performance in order to determine the optimum fuel burn. However, the FDR data available in this analysis, coupled to an aircraft performance model allows some of these challenges to be overcome and provides an opportunity to explore what additional insights can be gained through a fuel-based inefficiency analysis. The FDR data was from Swiss A319/A320/A321 aircraft types serving European destinations, and hence this aircraft family and geographic region was the focus of this part of the analysis. Note that this type of analysis is on-going and only the challenges and preliminary findings from a limited set of data analysis are presented here as part of the Omega study.

In terms of aircraft performance models, two models were assessed for this analysis: Eurocontrol's BADA (previously used for the airspace charging analysis) and Lissys Ltd's Piano-X [Lissys, 2008]. Comparison of each model outputs with FDR data was conducted: results from one representative flight are given in Figure 11 in terms of fuel burn as a function of distance flown. It is apparent that the Piano-X output is a better match to the FDR data than BADA (although performance during the descent phase is less good: see discussion later). The former model had an advantage for this application because weight and target cruise altitude/speed are inputs so could be matched to the actual trajectory (as could be done if such states were available in a future surveillance system). BADA, however, uses relatively more rigid standard trajectory definitions where only the target cruise altitude can be easily specified. Therefore, for this part of the analysis, it was deemed appropriate to use the Piano-X model to predict the optimum fuel burns for comparison with the observations from the FDR data.

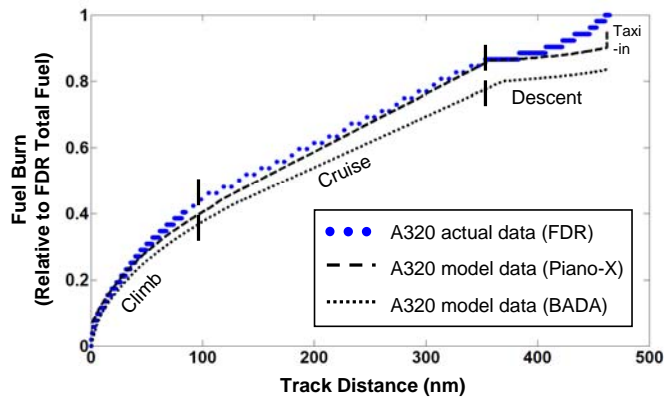


Figure 11: Aircraft Performance Model/FDR Data Comparison

Even with such an aircraft performance model, it is still a challenge to determine the optimum fuel burn (which is the baseline for the fuel-based inefficiency analysis) on any given route. This is because, in addition to aircraft type, weight and route length (which are known in the analysis here from the FDR data), optimum fuel also depends on a number of other factors (which are unknown), such as winds, temperature, the aircraft's centre of gravity and the operator's "cost index" [Airbus, 1998]. This is the ratio of time-related costs per minute of flight relative to the fuel-related costs per kg of fuel burnt. The priority of one over the other varies from one operator to another and can be entered into a modern aircraft's flight management system (FMS). The choice of cost index affects the optimum fuel burn, as shown in Figure 12 for the case of a representative 1000 nm mission.

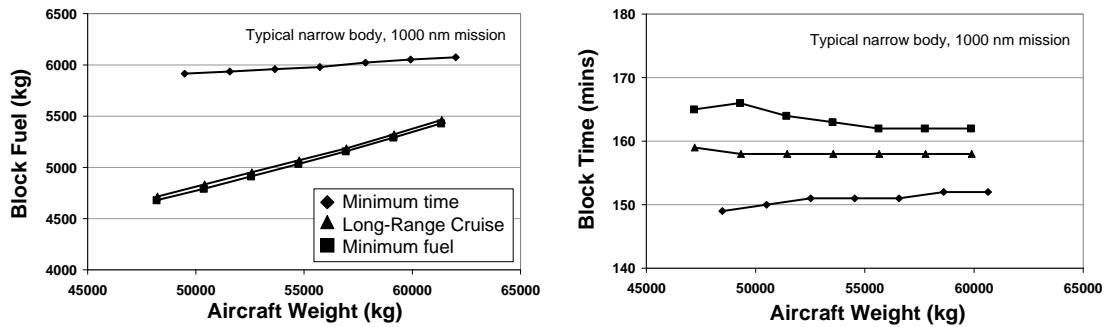


Figure 12: Time/Fuel Prioritization Impacts

With a very high cost index in the FMS, reducing time costs are prioritized and hence a minimum time (maximum speed) profile is flown, and this has a fuel burn penalty. By contrast, a low cost index prioritizes minimizing fuel (maximizing range), which has a time penalty. In between these extremes, the fuel and time responses are not linear and many operators opt to fly a "Long Range Cruise" cost index which gives a speed at which 99% of the maximum range is achieved. This is seen in Figure 12 to be a compromise between the two extremes in terms of time, but which enables most of the fuel benefit to be achieved. For this analysis, the optimal fuel burn was taken

to be the minimum theoretical fuel given by the model, but the limitations described above (e.g. zero wind is assumed throughout) need to be considered when interpreting the results.

For clarity, results for one specific route in the FDR data are presented in detail: London Heathrow to Zurich (future publications will contain details of the European-wide analysis). This route was chosen because it was closest in length to the average across all routes in the lateral analysis. The lateral results for that route were virtually identical to the Europe-wide analysis. The aircraft performance model was used to determine minimum theoretical fuel burn in total and in each of the flight phases, i.e. departure terminal area (within 50 nm of the departure airport), en route and arrival terminal areas (within 50 nm of the arrival airport), so the fuel inefficiency could be studied by flight phase for direct comparison with the lateral analysis presented earlier. The comparative results are presented in Figure 13.

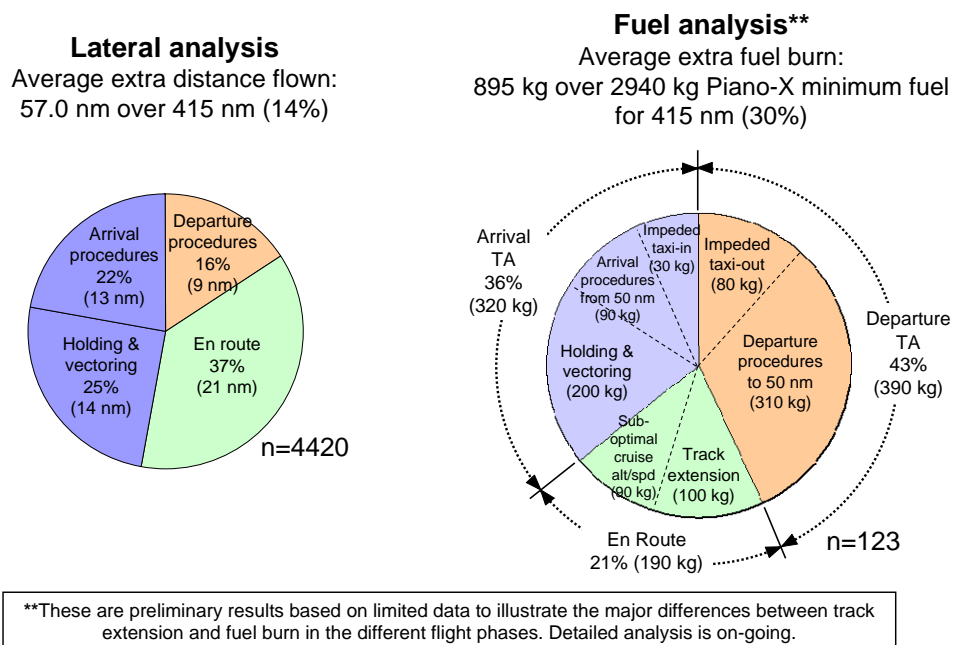


Figure 13: Lateral and Fuel-Based Inefficiency Comparison

Due to the limited number of flights used in the fuel-based analysis, caution should be used in generalising the results too broadly, but some general observations are given to illustrate some of the insights that can be gained through this type of analysis. There are a number of differences apparent between the lateral and fuel-based results. Firstly, the aggregate fuel inefficiency is about double the lateral inefficiency at 30%, i.e. 30% more fuel was burnt on average in these flights compared to the minimum theoretical fuel burn on the route from the aircraft performance model. This indicates that the total extra fuel burn is not proportional to the total extra track distance flown: it appears to be significantly greater. The fuel inefficiency split across the flight phases is also very different, with the relative importance of the departure terminal area inefficiency being much greater. This is due to a

combination of two factors. Firstly, because the fuel burn rate is so high in the initial climb phase (see Figure 11), even the relatively small amount of track extension in that phase due to the standard departure procedures leads to significantly greater fuel burn within 50 nm of the departure airport compared to the theoretical minimum. (Note that the extra fuel burn could also be due to non-optimal vertical and speed profiles within the initial climb segments, but this was not explicitly considered). Secondly, the fuel-based metrics now include taxi-out fuel, so ground inefficiency is also being captured in these results whereas this was not possible with the lateral metric. (Note that the unimpeded taxi-out time was taken to be standard value of 7.5 min as used in Piano-X, but this would need to be tailored to individual airports for a more accurate assessment of taxi fuel inefficiency). In the en route phase, the extra fuel burn can be attributed to two primary factors: using the typical fuel burn per nautical mile in cruise from the aircraft performance model, about half of the observed extra fuel burn is due to en route track extension. The other half is a result of sub-optimal cruise altitude and speed for the aircraft. Note that the route analyzed here was a relatively short one: the importance of the en route phase on longer routes will get proportionately larger. In the arrival terminal area, the fuel burn rate is relatively low in a typical descent phase when the engines are near flight idle. However, engine thrust increases are required to execute a holding pattern, and this is the cause of most of the extra fuel burn in this phase, despite the fact that holding/vectoring accounted for only half the track extension identified through the lateral analysis. As for the departure, the results now also include taxi-in impacts (but again these are against a “standard” unimpeded taxi-in time of 5 mins).

So it is seen that the fuel-based analysis provides a number of additional insights that were not possible with the lateral analysis (e.g. impacts of vertical/speed profile and taxi operations), as well as a different interpretation on the relative importance of different flight phases. The fuel-based results could therefore be argued to be more relevant to environmental performance assessment. But there are a number of important caveats to the fuel-based results which need to be considered when interpreting their meaning. Firstly, as noted previously, these results are based on a limited set of analysis given the scope of the project. A very much longer route, for example, would have a very much larger contribution from the en route phase. Secondly, and the biggest challenge overall, is the modelling of optimum fuel burn and any errors in that modelled optimum could manifest as additional inefficiencies. The biggest performance modelling challenges exist in the landing and take-off (LTO) cycle, and hence any errors in the modelled performance during the climb phase will have an important impact on the results. It is also difficult to know what the unimpeded taxi fuel is and airport-specific studies would be required to capture this aspect accurately.

Overall, these results demonstrate the significant insights that can be gained through the use of fuel-based analysis, but significant on-going research is required to refine the methodology.

3.0 Environmental Impact Implications

By definition, the inefficiencies described in the preceding section quantify how far an aircraft is flying from its optimal profile and hence affect the environmental impacts of aviation. The optimal profile from an environmental performance perspective depends on the environmental impact of interest (e.g. noise, air quality, climate change). For example, a trajectory that minimises noise impacts may require an aircraft to fly a longer ground track in order to avoid regions of high population density, and hence burn more fuel with greater climate change impacts. Similarly, an engine that is optimised for low air quality impacts may be noisier or less fuel efficient compared to a standard engine. There are also trade-offs within an environmental impact: for example, both CO₂ and contrails have impacts on climate change, while techniques for reducing contrails by flying around a contrail-forming region may increase fuel burn. While recognising these important interdependencies between and within different environmental impacts, this Omega study focuses primarily on climate change effects. But a brief qualitative discussion of the impacts of flight inefficiencies to the other environmental factors is included below where relevant.

The fuel-based analysis has indicated that aircraft burn more total fuel on a given route than the theoretical minimum. Hence the total emissions are also greater: the extra CO₂ emissions are in direct proportion to the extra fuel burn, while the effect on pollutants such as NO_x are more difficult to quantify because they depend not only on the amount of fuel burnt, but also the engine settings and atmospheric conditions at the time of the extra fuel burn. This affects the analysis of climate change impacts from aviation, such as the original IPCC report previously discussed [IPCC, 1999], as well as the updated IPCC results [Sausen et al., 2005] illustrated in Figure 14.

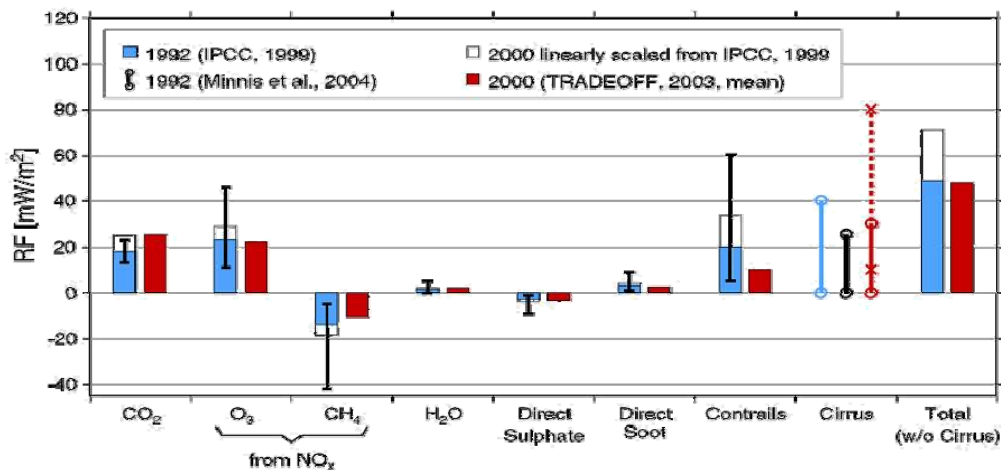


Figure 14: Aviation Radiative Forcing Assessment [Sausen et al, 2005]

The original and the updated IPCC results both attempted to account for flight inefficiencies due to ATM by scaling up the radiative forcing estimates for the various species by a factor of 1.15, while the factor falls to 1.05 from 2015 to account for ATM improvements after that time. Although the 1.15 factor

appears consistent with the results from this (and many others) lateral analyses based on track extension, it appears low (by a factor of up to two) relative to the preliminary fuel-based analysis. As previously discussed, more work is needed to verify this analysis, but these results suggest that the IPCC analysis and its update may be underestimating the contribution of ATM and hence underestimating the radiative forcing impacts of the species shown in Figure 14. Note that the lateral analysis in terms of extra distance flown does have a direct impact on the prediction of effects of contrails: the greater the distance flown in a contrail-forming region, the greater the size and likely environmental impact of the contrails. Hence the 1.15 factor used in the IPCC studies may be appropriate for contrail impact prediction (although this impact continues to be one where the uncertainty levels are very high).

It was also observed in the fuel-based analysis that the extra fuel burn is not evenly spread among the different flight phases. A disproportionate amount of extra fuel burn (compared to extra distance flown) occurs in the terminal areas and hence at lower altitudes. Although this does not affect the environmental impacts of the CO₂ due to its very long lifetimes (and hence, over time, it becomes mixed over a global scale), it does affect the climate change and local air quality impacts of some other pollutants, such as NO_x. Figure 15 shows that a 5% increase in the NO_x emissions has a very different radiative forcing effect depending on the altitude at which the emissions occur [Köhler et al., 2008]. A greater proportion of emissions nearer the surface are also likely to have local air quality impacts due to concentration changes on the ground.

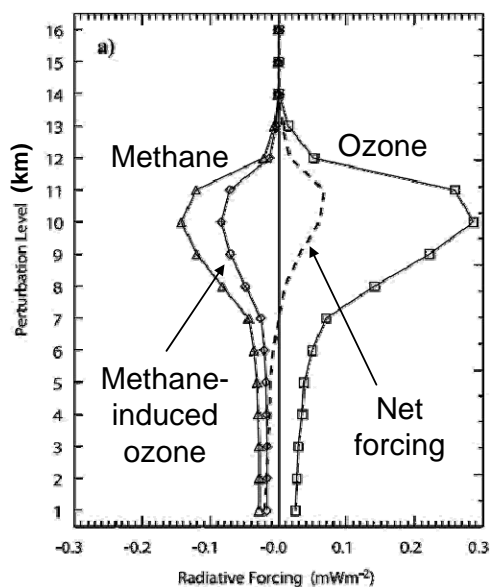


Figure 15: Radiative Forcing Changes due to 5% NO_x Change at Different Altitudes [Köhler et al, 2008]

A detailed assessment of the actual environmental impact of flight inefficiency is beyond the scope of the current Omega project. However, the discussion above highlights the fundamental importance of close collaboration between

ATM researchers, climate scientists and local air quality modellers if a realistic assessment of the environmental impacts of aviation is to be made (e.g. accurate factors are used in climate modelling emissions inventories to account for ATM effects).

In terms of other environmental impacts, the constraints of aircraft trajectories that cause the flight inefficiencies can affect the ability to accommodate "best practise" operational techniques. On departure, a Continuous Climb Departure (CCD) is often desired whereby level segments are eliminated as much as possible. This gets aircraft as high as possible as quickly as possible, reducing noise and local air quality impacts on the ground, and getting the aircraft to the more fuel efficient cruise altitudes earlier. However, constraints such as airspace limitations or the need to accommodate arrival and/or departure flows from other nearby airports often mean that CCDs are difficult to accomplish in the current system. In the cruise phase, it is often desirable to allow aircraft to fly their preferred routings, altitudes and speeds (so-called "user-preferred trajectories") since this is often the optimal profile given they have complete knowledge of the state of their aircraft, winds and operator objectives. Although these preferences can often be accommodated at times of low demand (such as late at night), the need to accommodate large numbers of aircraft in a given amount of airspace at other times requires aircraft to fly standardised routes/altitudes/speeds. This makes the ATM task more manageable but increases the inefficiencies. On approach, best practise techniques of Continuous Descent Approaches (CDAs) and Low Power/Low Drag (LP/LD) can help reduce noise and fuel burn simultaneously. Similar to CCDs, CDAs aim to keep the aircraft as high as possible and at as low thrust as possible for as long as possible by eliminating levels segments from top of descent all the way to the final approach. But as with the other flight phases discussed above, accommodating them in a busy air traffic system is difficult to accomplish. Future ATM design may enable more widespread use of these techniques in the future despite increases in traffic levels, as discussed in the next section.

4.0 ATM Evolution Implications

4.1 Implications for Future ATM Design

The findings discussed above give pointers towards appropriate priorities for future ATM designs to reduce flight inefficiency. Table 2 presents the inefficiency sources that have already been introduced in the preceding sections, along with ATM improvement options that would help reduce them.

Table 2: Implications of Flight Efficiency Analysis on Future ATM Evolution

Inefficiency Source	ATM Improvement Options
Taxi-out, Departure procedures	Optimal taxi-out procedures, take-off & climb profiles
Standard routes/flight levels/speeds	4D trajectory management for user-preferred trajectories
Restricted airspace	Minimising restricted areas
Adverse weather	Better forecasting/detection
Congested airspace	4D trajectory management, increase airspace capacity
Expensive airspace	ATM charging harmonisation
Arrival holding & vectoring	4D trajectory management
Arrival procedures, Taxi-in	Optimal arrival profiles (CDA, LP/LD), optimal taxi-in procedures

In terms of departure procedures, taxi-out operations can be improved through better automation, such as optimised push-back time and sequence to minimise holding on the taxiways, followed by an engine power optimised take-off procedure. There is little there can be done about the extra flight distance resulting from the need to take-off aligned with the departure runway and then turn towards the destination airport. But the climb profiles in terms of altitude and speed profiles that are closer to optimal (e.g. Continuous Climb Departures) should be targeted in future ATM designs.

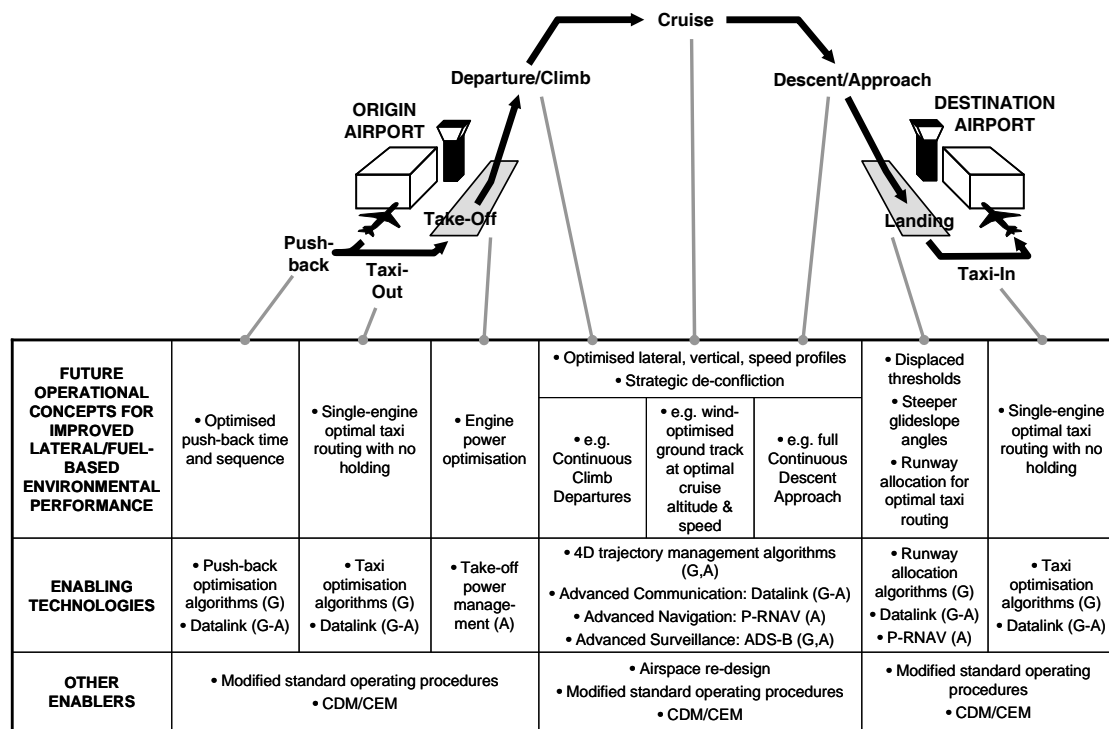
En route structure that imposes standardised routes, altitudes and speeds in order to manage the complexity for the air traffic controllers was identified as a major cause of inefficiency in the en route flight phase. This inefficiency could be improved through operating paradigms that allow more widespread use of flight away from the rigid airway structure, as proposed in many "free flight" or user-preferred trajectory concepts (SESAR and NextGen initiatives). There are many studies to assess how this removal of airspace structure affects the air traffic control process, and this needs to be carefully considered to maintain safety at high levels. But if such concerns can be addressed, these strategies would improve efficiency in both the en route and oceanic airspace. ATM systems based around 4D trajectory management with automated de-confliction tools should allow greater use of user-preferred trajectories that get closer to each flights ideal lateral, vertical and speed profiles. Congested airspace related inefficiency should also be helped by 4-dimensional trajectory management. However, the relationship between traffic levels (which are likely to continue to increase in the future), airspace capacity and congestion-related inefficiency is highly complex and will need further research. In the ultimate 4D trajectory management ATM system, there should be little need for holding or vectoring of aircraft. Delays could be

forecast far in advance of an aircraft's arrival into the terminal area, allowing a more efficient accommodation of delay. For example, by slowing the cruise speed of an aircraft by a few knots on a long distance flight to manage its arrival into the terminal area at a pre-determined time when it can be accepted without delay is much more efficient than having aircraft enter the terminal area at an unplanned time, then holding them until a runway slot is available. Currently there are also Communication, Navigation and Surveillance (CNS) limitations in en route and oceanic airspace in many parts of the world. There are moves in the US and Europe to transition away from the legacy system design of VHF radio communication, ground-based navigation and radar surveillance to more sophisticated infrastructures involving datalink communication, satellite-based navigation and aircraft-based automatic dependent surveillance. These technologies should enable inefficiencies in these regions to be reduced to handle the forecast traffic growth, for example by reducing separation minima by implementing aircraft self-separation and automated conflict detection and resolution. Traffic is growing most rapidly in some parts of the world where the current infrastructure is unlikely to be able to accommodate it (e.g. India and China). However, it is likely that technological advances and global ATM harmonization efforts will enable step-changes in CNS capability in these regions instead of the slow incremental evolution observed in the more developed regions of the world where growth has been more gradual. Minimising the amount of restricted airspace that needs to be avoided, better forecasting and detection of adverse weather, and minimising airspace charging differentials between neighbouring airspace should all assist in reducing these as major inefficiency sources.

As for the standard departure procedures, there is little that can be done to reduce the extra flight distance required to safely align with the arrival runway orientation without major upgrades to the guidance systems that may permit, for example, curved approaches. But arrival procedures allowing Continuous Descent Approaches from as high an altitude as possible should be prioritised and will be helped with 4D trajectory management. Enabling aircraft to do this during the entire descent and approach phases can reduce fuel burn and associated emissions during the descent phase by as much as 50% per flight compared to a standard descent and approach, while peak noise is also reduced by 3-6 dBA per flight in some regions. Landing further down a runway ("displaced thresholds"), steeper approach angles and runway allocation for optimal taxi routing are all advanced techniques that will also lead to environmental impact reduction, but these are longer term initiatives.

The discussions above illustrate that there is significant scope for ATM advanced technologies and procedures to improve environmental performance of the air transportation system. The main initiatives that could improve lateral and fuel-based environmental performance in different flight phase are summarized in Figure 16, along with enabling technologies. European and US plans for major ATM improvement in the future (i.e. SESAR and NextGen) incorporate many of the improvements suggested which, if

implemented in a timely and integrated fashion, should enable per flight reductions in fuel burn and associated emissions due to ATM of at least 10%.



Key: (G) = Ground, (A) = Aircraft, (G-A) = Ground to Aircraft, ADS-B = Automatic Dependent Surveillance-Broadcast, CDM = Collaborative Decision Making, CEM = Collaborative Environment Management, P-RNAV = Precision Area Navigation,

Figure 16: Future ATM Concepts Summary

4.2 Residual Inefficiency

ATM evolution alone cannot address all of the inefficiencies identified, i.e. some “residual inefficiencies” would remain due to fundamental constraints, and the fact that the inefficiency cannot be entirely attributable to ATM. These include the need to keep aircraft safely separated from each other, as well as adverse weather and terrain, although it could be argued that CNS improvements will reduce (but not eliminate) their impacts. For example, surveillance improvements may enable separation minima to be reduced without adversely affecting safety. This residual inefficiency caused by the need to keep aircraft safely separated is likely to take in increasing importance due to continued growth in traffic demand, and hence growing congestion. Congestion was identified as an important contributor to flight inefficiency in the current system, and its importance is likely to increase in the future without major capacity enhancements. Capacity is needed on the ground and in the air, through added infrastructure (e.g. runways and airspace), technological investment and procedural changes that allow more efficient use of the capacity that is available. Even then, the aggregate emissions from aviation are set to increase in the coming decades because traffic growth will exceed the possible efficiency gains (even given aircraft technological improvements). The fundamental interplay between safety, capacity and environmental performance is highlighted by this discussion.

The reality of requirements of multiple users of airspace (e.g. commercial, general aviation, military, etc.) means that there will always need to be restrictions to the controlled airspace for the exclusive use of commercial aircraft. Wholesale removal of restricted airspace is unrealistic and hence this is another source of residual inefficiency, but minimising the extent and/or times of use of these restricted regions would help the environmental performance of the commercial ATM system.

The need to consider multiple, and sometimes competing, environmental issues at once could also be considered a type of residual inefficiency. For example, departure and arrival procedures that involve longer routes (and hence greater fuel burn and climate change effects) to minimise noise effects will manifest as non-optimal in terms of one environmental impact, but may be the best compromise option.

4.3 Barriers to an Optimal ATM

Apart from the residual inefficiencies identified in the preceding section, there are other barriers to progress towards an optimum ATM system. Many of the ATM improvement options discussed in Section 4.1 rely on advanced technology development, the pace of which is uncertain. Similarly, development of procedures which take full advantage of the new technologies often take a considerable amount of time. Indeed, the pace of procedural development in the past has lagged the technological capabilities within the system by a significant period (e.g. some separation minima are the same today as they were 50 years ago). This will require a collaborative effort involving all stakeholders: incentivising the necessary change is another major institutional barrier if system performance is to be improved in the face of growing demand in the future. Other barriers to change include political will to harmonise airspace (as in SESAR or to eliminate airspace charging differentials) and the requirements of other airspace users such as military and general aviation whose requirements also need to be seriously considered. Controller and pilot workload also have fundamental limits which affect future system design: the affects of modified technologies and procedures on these groups need to be carefully considered in light of these limits. Finally, arrival holding/vectoring was identified as a major issue in both the lateral and fuel-based analyses. Limited airport capacity causing arrival delay is the root cause of this issue. Planned increases in airport capacity are unlikely to keep pace with growth in aircraft movements, and hence it will become increasingly important to manage arrival delay in a more environmentally-friendly way. The importance of airport capacity in considerations of inefficiency within Europe is the subject of the next Section.

5.0 European Airport Capacity Analysis

The flight inefficiency analysis and discussions presented in the preceding sections has highlighted the importance of holding/vectoring in the arrival terminal area: it accounted for around a quarter of the total extra distance flown and extra fuel burn on average. Holding absorbs delay due to limited runway capacity *and* provides a ready pool of landing aircraft so the controllers can maximise the throughput on the runways, while vectoring is used for spacing and sequencing of traffic on final approach. In all cases, airport capacity is a primary driver of the need for holding and vectoring. A harmonised assessment of airport capacity in Europe, now and in the future, is not readily available in the open literature. A European airport capacity assessment was undertaken as part of this Omega study, which was then used to understand how capacity may need to evolve in the future relative to projected demand growth and hence better understand the holding/vectoring inefficiency source.

5.1 Literature review

A comprehensive review of the recent literature on airport capacity in Europe from an ATM system perspective can be found in [Desart, 2007]. Much of the following section is based on that work.

5.1.1 European Airports Background

In Europe, ICAO records 2,234 airports in 36 countries who are members of Eurocontrol, of which 1,986 are in 25 countries of the European Union [SESAR, 2006a]. Of these, 766 are recognised by IATA as commercial airports. In 2004 these airports accounted for 1.23 billion passengers together with 15.5 million tonnes of cargo and a total of 17.7 million air transport movements (ATMs). About 23,000 Instrument Flight Rules (IFR) flights were accommodated during peak days over the ECAC (European Civil Aviation Conference) area in 1993; while a new daily record of 33,500 flights was set in 2007 [Eurocontrol, 2007]. The overall demand for air transport is expected to increase by 2.7-3.7% per annum until 2025 [Eurocontrol, 2006]. As a result, it is anticipated that by 2025 the annual European traffic demand will be 1.7-2.1 times that of 2005 (ibid, 2006). Under the high growth scenario, the 9.1 million IFR flights in 2005 will increase to nearly 19 million IFR flights by 2025 [SESAR, 2006b; Eurocontrol, 2006]. During the busiest months of the year, the European ATM system should be able to accommodate 50,000 flights a day around 2022.

Growth at high-density airports is heavily constrained by physical and environmental factors. The 35 largest European airports were estimated to have reached saturation in 2005. With regional airports working at full capacity, existing airport capacity in Europe will be reached between 2013 and 2015 [SESAR 2006a]. If traffic demand doubles between 2005 and 2020, some European airports will struggle to accommodate such growth. According to [Eurocontrol, 2004], about 60 airports will be congested by 2020, and the top 20 airports will be saturated for between 8 and 10 hours a day.

There is therefore a clear need to create more capacity to ensure that the European economy remains competitive and to ensure the most efficient ATM operations. Building new runways and terminals is an obvious solution to capacity provision, but it is also by far the most expensive. In addition, very few new airports are expected to be developed in Europe over the next 20 years. Other solutions therefore consist of developing new technologies and procedures that can optimise the use of available airport capacity. In Europe, the utilisation of airports varies significantly; some have capacity shortages whereas many do not.

5.1.2 Airport Capacity Definitions

One problem encountered when assessing future airport capacity needs is the lack of consistent data on the *current* capacities in Europe. This is partly because there are many definitions of airport capacity. In Europe, each major airport (also known as scheduled or slot controlled airports) is required to declare their capacity as part of the slot scheduling, air traffic flow management (ATFM) regulation and airport coordination process [European Commission, 2004]. But as [de Neufville & Odoni, 2003] note, there is no generally accepted definition of declared capacity and no standard methodology for setting it. It is essentially the responsibility of each airport, under guidance from its civil aviation organisation, to set its own capacity and to self-report it. As a result, declared capacities vary from airport to airport, EU member state to member state. There is no independent audit of these self-declared capacities and in many cases little supporting evidence to verify the veracity of the calculations. As a result, a system-wide analysis of future airport needs to begin with a harmonised assessment of current airport capacities to act as a baseline.

Two additional concepts of capacity are also commonly used: ultimate capacity and practical capacity. Ultimate capacity - also called unconstrained capacity - is achieved when, under constant demand, the spacing between flights fits the minimum air traffic flow management (ATFM) separation rules. In such a case, the system is continuously and steadily fed by arrivals or departures, and each flight is served in the minimum time without idle periods. According to [Newell, 1979], capacity must be uniquely specified by a variety of subsidiary conditions such as the single runway occupancy rule or the separation minima imposed by a wake vortex constraint. A similar definition of ultimate capacity is used by [Janic, 2000]. Considering an airport as a service provider, capacity reflects the quantity of service that can be produced and delivered during a given period of time and under given conditions. In other words, ultimate capacity is expressed as the maximum number of entities (ATM movements, passengers, etc) that can be served or accommodated in a given period of time (typically on an hourly basis) under conditions of constant and continuous demand for service.

The concept of practical capacity – also called operational, saturation or sustainable capacity – is intrinsically based on a certain level of service. [Newell, 1979] defines sustained capacity as a maximum average flow that a

facility can accommodate over a time period long enough to include a large count (say 100 or more) and which could, in principle, be sustained for an infinitely long time. Practical capacity is also defined as the maximum number of entities that can be served in a given period of time under conditions when the average delay imposed on each entity does not exceed a level prescribed in advance [Hockaday & Kanafani, 1974; Horonjeff & McKelvey, 1994]. The paradox with the definition of operational capacity is that it can be changed – enhanced or reduced - by keeping all the factors affecting ultimate capacity unchanged (infrastructure, ATC equipment or operational procedures), but varying the acceptable level of delay. In this way, a major European airport increased capacity by 8% during peaks by increasing the acceptable level of delay from 4 to 8 minutes, everything else remaining unchanged.

5.2 Harmonising European Capacity Estimates

Airport capacity can be estimated and simulated using a wide range of methods. The history of air traffic flow management analysis and optimisation started in the late 1950's in the US where airport capacity was expressed by two or more separate, independent and high-level values, one for arrival capacity, another for departure capacity, and sometimes for a mixed mode of operations composed of successive arrival/departure sequences, resulting in the publication of the FAA airport capacity handbook [FAA, 1983].

Considering only one capacity value probably results from the fact that, for most planning and operational purposes, capacity is assumed to be relatively stable over some given period [Janic, 2000]. At many airports, those independent values have been determined by ATFM operators using either informed guess-work, rule of thumb, or by simply counting the number of ATM movements accommodated at a specific airport during a given time interval.

The advantages of these methods reside in the fact that they are simple to use and do not require any expertise in airport modelling and/or planning, nor do they require much operational data. They are aimed at producing charts and calculations for the purpose of airport operators and users where the expertise required is the ability to look up numbers in those charts and calculations.

Since these charts were generated, many other approaches have been developed. There are analytical models based in theoretical spacings, speeds and controller behaviour. There are also digital simulation models which can be fed with full geometric airport data and nominal aircraft schedules as well as the above operational characteristics. These models can generate highly realistic representations of actual operations, calculate average delays over a specific time interval and identify pinch points on the airport. They are, however, much too data-hungry and time-consuming to be used in this study.

Thirty-five major airports in Europe were considered for more detailed analysis in this study. Of those, 13 have one operational runway (e.g., London

Gatwick, Stuttgart, Geneva), 10 have two (e.g., Oslo, London Heathrow, Athens), nine have three (e.g., Frankfurt, Barcelona, Zurich) and three have four or more operational runways (e.g., Paris CDG, Madrid, Amsterdam). Given the problems of identifying a coherent set of data for the top 35 European airports, the decision was taken to estimate daytime hourly capacities using a combination of available data, expert judgment and informed guesswork. The resulting estimated capacities have been based on the guidance provided by the Federal Aviation Administration [FAA, 1983; FAA, 2002] and reproduced in [Horonjeff & McKelvey, 1994]. These charts cover a variety of runway configurations and fleet mixes for both VFR and IFR operations for balanced arrivals and departures, and they presume non-segregated operations on pairs of widely spaced parallel runways (i.e. each runway accepting landings and takeoffs in the same hour). IFR operations with a fleet mix of 80% light jets and 20% heavy jets have been taken as the norm for this part of the study.

The FAA handbook estimates of capacity have been checked against the achieved capacities at the best-in-class airports for given runway configurations. The best-in-class airports are taken as: London Gatwick for single runways, Frankfurt for close parallel runways (making allowance for the additional open V runway) and London Heathrow for the more widely spaced parallel runways (operating in segregated mode). These airports are known for optimising their taxiways and runway exits, and for the use of High Intensity Runway Operations (HIRO).

Three capacity estimates have been calculated: (i) a realistic estimate for comparison with currently declared capacities; (ii) a minimum likely estimate; and (iii) a potential estimate which is intended to reflect use of best practice in design of taxiways and exits, together with maximum use of HIRO while generally still respecting known noise abatement preferences. Each set relates to daytime operations and constraints. A fair amount of informed judgment has been used in deriving these estimates, to cope with runway configurations not quite matching those on which the charts are based, or the value of more taxiways or runway exits, or the use of HIRO.

It is considered that these estimates will be generally correct to within 5 ATM/hour, but there are many caveats which must be taken into account. These are:

- The fleet mix at specific airports may well differ from that assumed above (e.g. for airports that are mostly used for holiday charter or by low cost carriers).
- There may well be a serious imbalance between arrivals and departures in peak periods, particularly at those airports subject to hubbing operations.
- Jeppeson manuals have been used for the runway layout information and for the operating procedures. It is not always clear

which runway configurations are used simultaneously, nor how rigorously the noise abatement preferences are applied.

- There are no data on wind strength or direction immediately available, so it is possible that the runway configurations adopted for this study are not appropriate on sufficient occasions to allow them to be used as a basis for declared capacity.
- There may well be other constraints that would control the declarable capacity: terminals, aprons, terminal airspace conflicts, radar capability, air traffic controller staffing: these have not been considered here.
- Declared capacities usually have ranges rather than single numbers, reflecting the changing fleet mix and the balance between arrivals and departures, as well as periods for catching up between peaks. For comparison with estimates, these ranges have been reduced to a single figure, but that figure may not be properly representative of the runway configuration or fleet mix on which the estimates were made.

Many of these caveats could be lifted or clarified in discussion with the respective airport operations managers and/or the senior air traffic controllers, thus improving the confidence in the estimates substantially. Any further improvements would, however, need extensive data collection and model-building.

Four types of airport runway configurations have been analysed:

- Widely spaced parallel runways (12 in data set)
- Close parallel runways (9 in data set)
- Multiple non-parallel runways (9 in data set); and
- Single runways (5 in data set)

In the widely spaced parallel runway category, most of the 12 airports have additional runways, including all those declaring the same or greater capacity as London Heathrow. As shown in Figure 17, there is excellent agreement between estimated and declared capacity except for rather low declarations at Athens and Palma and a very low declaration at Budapest.

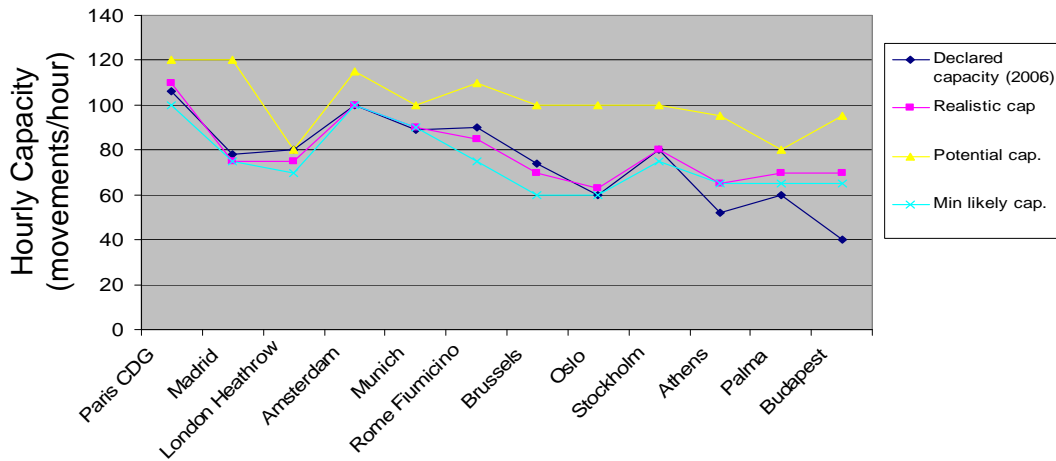


Figure 17: Hourly Capacities for Wide Parallel Runways

In the close parallel runway category, many of the nine airports also have additional cross or open V runways. It is difficult to make good estimates of the value of these additional runways because of lack of information on wind and the local judgments of controllers on the viability of combined operations. As shown in Figure 18, Milan Malpensa (without an additional runway) and Copenhagen both declare 10 ATM/hour more than estimated while Dusseldorf is 10 ATM/hour below the estimate. Agreement for the other airports is good.

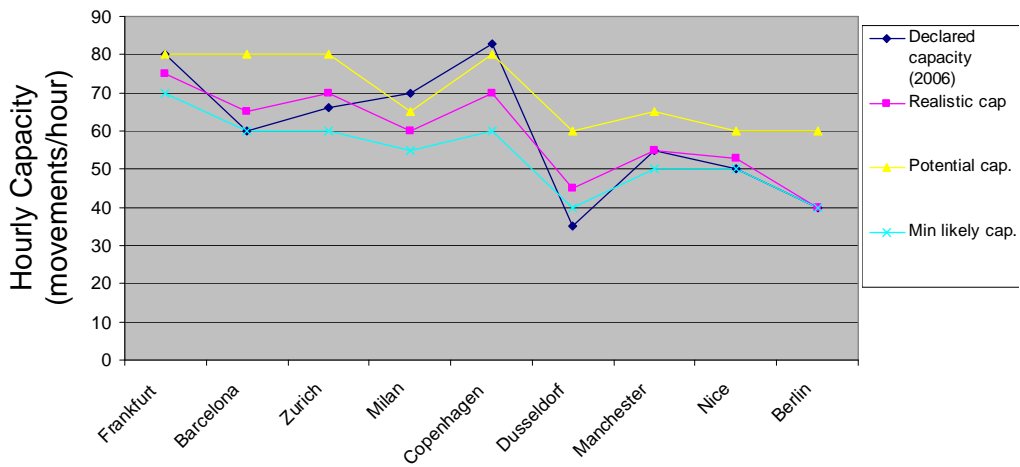


Figure 18: Hourly Capacities for Close Parallel Runways

The nine airports in the multiple non-parallel runway category have a diverse range of configurations, making it impossible to choose a best-in-class airport. As shown in Figure 19, however, agreement between the declared and estimated capacities is again good, except for Istanbul and Warsaw which both declare 15 ATM/hour less than the estimates.

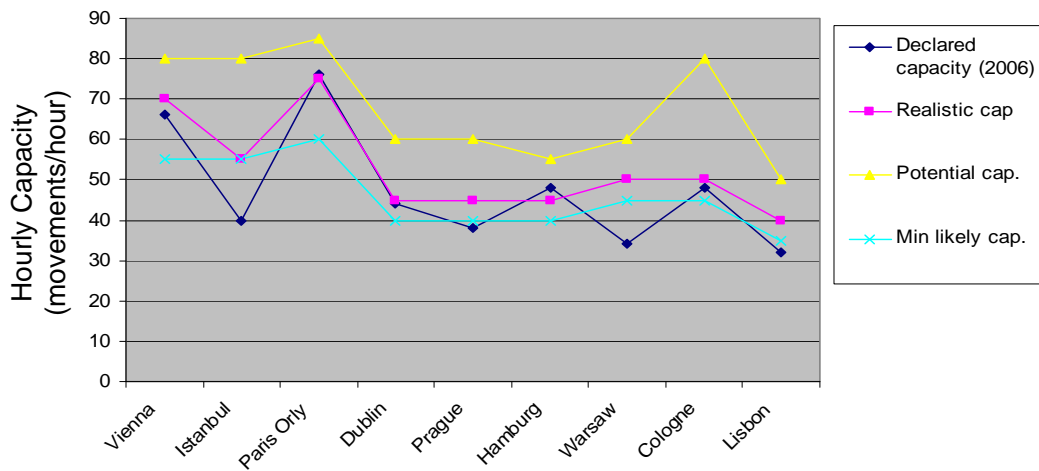


Figure 19: Hourly Capacities for Two or More Non-Parallel Runways

In the single runway category, estimates agree almost precisely with the declared capacities for all five airports. As shown in Figure 20, there is a difference of 20% between the worst and the best-in-class, with Gatwick achieving almost the maximum feasible level of capacity.

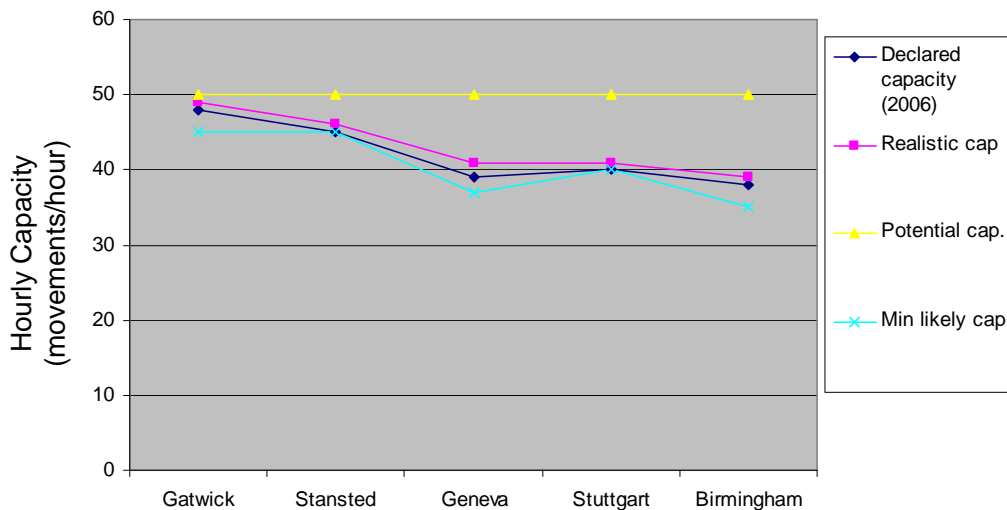


Figure 20: Hourly Capacities for Single Runways

5.3 System-Wide Modelling of European Airport Capacity Needs

The harmonised European airport capacity assessment described in the preceding sections was used in the University of Cambridge Aviation Integrated Modelling (AIM—see www.AIMproject.aero) project to assess future European capacity needs. AIM is a policy assessment tool designed to simulate the operation and economic/environmental effects of local and world airline networks over the next 30-50 years within a modular framework. It contains a set of inter-linked modules of the key elements of the air transport and environment system, including models for aircraft/engine technologies, air transport demand, airport activity and airspace operations, all coupled to global climate, local environment and economic impact blocks. Full details are given in [Reynolds et al., 2007]. Feedback between demand, capacity, air

traffic delays and policy measures is a key part of this model. Previous studies with the AIM framework have examined the airport capacity needs into the future in the US given the current baseline capacities and demand growth projections [Dray et al., 2008]. With the European capacity assessment described in the preceding sections, it was possible to undertake a similar assessment for the European system, and this will be described fully in a forthcoming paper. Demand growth was modelled using a simple one-equation gravity model with base year population, income, fare, travel time and air traffic delay data as the explanatory variables. Population and income inputs came from a set of internally consistent projections as defined in the Climate Change Science Program study [CCSP, 2007], while fare and travel time were based on analysis of current European data. The resulting demand projection for Europe in terms of Revenue Passenger Km for one of the CCSP scenarios (called IGSM) is illustrated in panel a) of Figure 21. The IGSM case was chosen because it gave projections closest to the Boeing and Airbus forecasts for the horizons over which they forecast. Under these demand projections, the capacity needs of the top 50 European airports were determined out to 2050 *which kept the average arrival delay at 2005 levels* using the “realistic capacity” estimate from the analysis described in the preceding sections as the 2005 capacity level. Note that the routing network was assumed to remain the same in 2050 as in 2005, i.e. the forecast demand was flights along the same routes, although the types and number of aircraft could change. In reality, by 2050 the routing network is likely to change in the face of changing demand distributions, airport capacity, business models (e.g. low cost carriers), etc., but capturing these aspects is beyond the scope of the current analysis.

The resulting increases in airport capacity at each of these airports to maintain a year 2005 average arrival delay in the year 2050 given the demand by that year are presented in panel b) of Figure 21. The area of the red circle is used to represent the capacity required in 2050 compared to the area of the blue circle representing the 2005 capacity. The capacity increase requirements are also shown as a bar chart in panel c) for the top 30 airports in terms of capacity needs in 2050. Under the assumptions used in this analysis, the current major airports are seen to require about a doubling of their hourly capacity, while some of the currently under-utilized airports can accommodate forecast demand growth with little or no capacity increases. Across the 30 airports shown, the average requirement was for a 1.68 times increase in capacity in 2050 compared to 2005 levels.

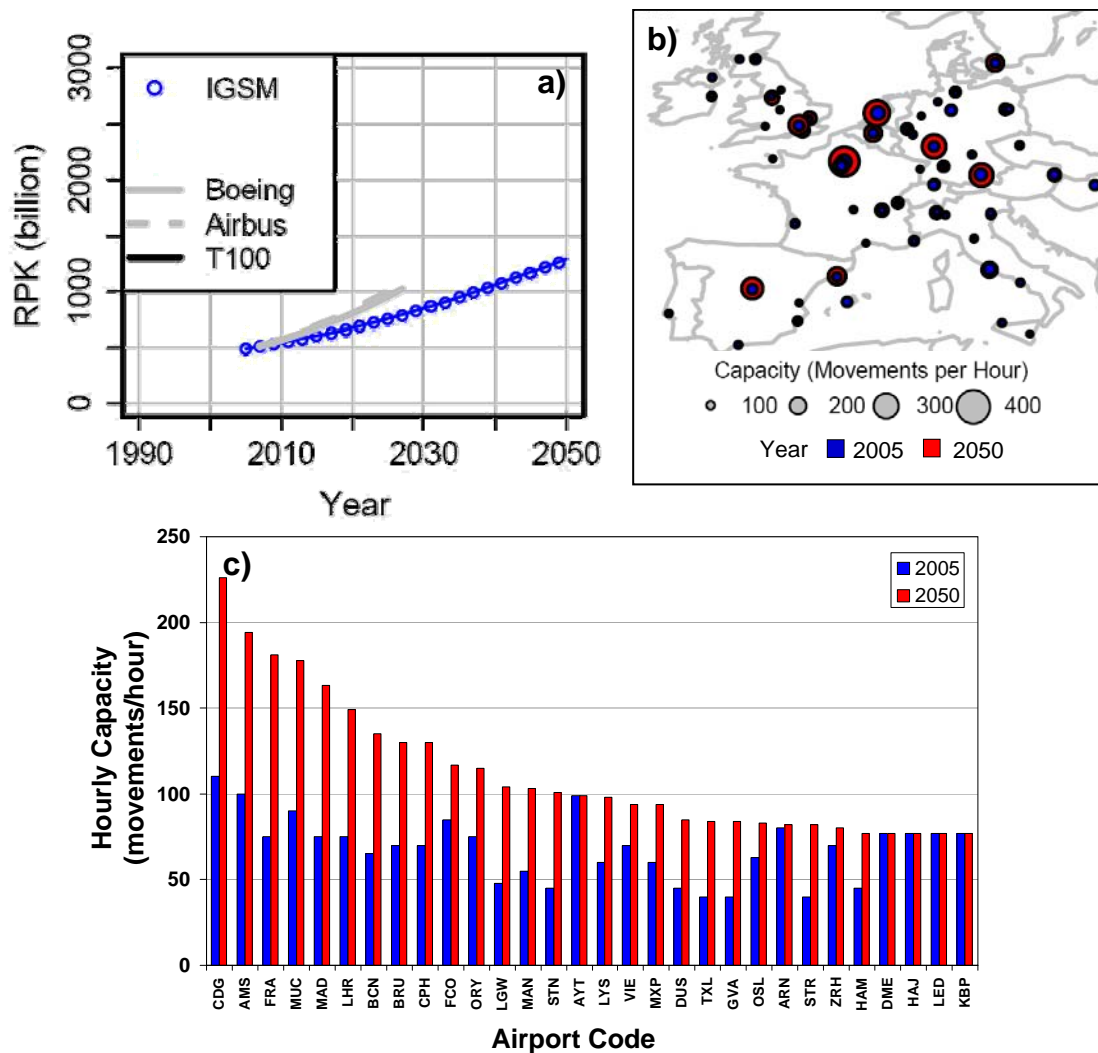


Figure 21: System-Wide Assessment of Future European Airport Capacity Needs

It is obviously important to interpret these results in light of the limitations of the analysis described, not least the assumption of unchanged routing network. In reality, adding airport capacity is difficult to accomplish, requiring either new runways at existing airport, new airports, or modified operating practices. Given the long lead times associated with all of these options, congestion is likely to increase in the future at some airport. High levels of delay can quickly become unsustainable as they cause schedules to fall apart, and this would prompt major behaviour changes from the system agents long before those delay levels were approached. One important example of behaviour change that is being considered by the AIM team is the adaptation of airline routing networks away from congested hubs or primary airports in a multi-airport system to less congested hub or secondary airports, while still satisfying the overall predicted demand levels. This is the focus of on-going research work within the AIM team.

In terms of the likelihood of meeting the increased capacity needs identified in this analysis, the Eurocontrol 'Challenges of Growth 2008' report [Eurocontrol, 2008b] proposes five basic methods that could be utilised:

schedule smoothing (moving flights to times of the day when capacity is available); moving excess traffic to secondary/regional airports; using larger aircraft to reduce daily frequencies on congested airport pairs; accelerate investment in high-speed rail networks; and exploiting the benefits of SESAR efficiencies to bring airports up to 'best in class' performance based on runway configuration. Of these five methods, it is considered that use of alternative airports could deliver a 25-40% reduction in un-accommodated demand and SESAR improvements could bring 40% gains. However, it is noted that these potential capacity gains would require a level of investment that is not reflected in current airport development plans. The report concludes that best results would probably come from a mix of these methods, taking into account different airline business models and local demand. However, the cautionary note is added that achieving the full effects ' . . . could require action to a degree that is unlikely to happen without legislative pressure' (p24).

Despite the limitations in the analysis highlighted, these results illustrate the challenges posed by airport capacity in the future. Just to maintain current levels of arrival delay, significant increases of airport capacity are required in the future. With the current ATM system in Europe, airport capacity limitations are likely to manifest as significantly greater inefficiencies in terms of holding/vectoring in the destination terminal area, en route congestion and even ground holding in the arrival terminal area. Only with increased airport capacity and a transition to future ATM along the lines highlighted in Section 4 is it likely that the dual challenges of handling increased traffic along with reduced environmental impact per flight will be met.

6.0 Conclusions & Future Needs

This study has undertaken a broad assessment of the importance of air traffic management to the environmental impacts of aviation. It has attempted to summarise the current state of the art, outlined recommended methodologies and undertaken new analysis to fill gaps and add knowledge in areas of need as identified by the stakeholder community, and communicated those findings through knowledge transfer activities.

The main conclusions that have emerged from this study can be summarised as:

- ATM has a fundamentally important part to play in reducing the environmental impacts of aviation.
- Flight inefficiency is an effective way of quantifying the current environmental performance of ATM and helping prioritise future evolution strategies.
- All phases of flight need to be considered: those in the terminal areas cannot be neglected due to the important flight inefficiencies in these regions.
- Fuel-based analysis, although more complicated to use, provides significant additional insights on flight inefficiency and resulting environmental impacts compared to the more common lateral-based analysis.
- Not all flight inefficiencies can be attributed to ATM and effective co-operation between stakeholders will be critical to removing these in the future.
- There are some residual inefficiencies that may not be possible to eliminate entirely due to fundamental constraints, such as the need to keep aircraft safely separated.
- Collaboration between stakeholders is of fundamental importance.

This Omega study has only been able to present a relatively broad assessment of the topic. There is much additional work that needs to be done in many areas, but the key ones flowing from this report are:

Additional Research Topics

- Need for more extensive flight data analysis comparing the fuel-based and lateral analysis to enhance the insights that can be gained from the use of the former.
- More work is needed to explore the fundamental relationships between safety, capacity, congestion and flight inefficiency.

Increased Collaboration

- Need for agreement on a consistent set of environmental performance metrics and analysis methodologies to harmonise the on-going efforts in this area within different stakeholder groups (which are currently inconsistent and hence difficult to compare).

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- Collaboration could be strengthened between many groups such as:
 - ATM researchers, climate scientists and local air quality modellers so a realistic assessment of the environmental impacts of aviation is to be made.
 - ATM researchers, airlines and air navigation service providers to facilitate access to operational data (with appropriate protections) which would support research work that would be of value to all parties.
 - Air navigation service providers, regulators, other airspace users (e.g. military) and service providers (e.g. weather data). Whilst there are lines of communication at the operational level, it is far from clear that there are connections at the research and analytical levels.
 - Having an independent venue for the sharing of knowledge amongst stakeholder groups against an agreed set of metrics, methodologies and data would facilitate these collaborations. Omega provides one option of such a venue.

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Appendix A: ATM Knowledge Transfer Activities

A.1 Stakeholder Engagement

Stakeholder engagement was considered especially important to Omega's air traffic management studies given that ATM activities affect, or are affected by, many different parties. These include the air navigation service providers themselves, as well as airlines, airports, regulators, NGOs, local communities, manufacturers, trade associations, academia, etc. Discussions with stakeholders and other knowledge transfer activities were on-going throughout the different stages of the project:

- The initial phase of the overall Omega activity focused on communications with key stakeholder representatives to determine gaps in current knowledge and anticipated future knowledge needs: the key questions that formed the basis of this ATM study were distilled from this activity and formed the basis for the study summary sheet that was available from the Omega website (see Figure A.1).
- During the study itself, the Omega researchers had regular meetings with key stakeholder representatives and industry groups (including CANSO, Eurocontrol, NATS, Federal Aviation Administration, Aviation Environment Federation, Farnborough Aerospace Consortium) to report on progress, get feedback to refine the work and maximise the potential value to those groups.
- A final knowledge transfer workshop was held to present the key findings of the project to stakeholders, and was also open to the press and general public. This event is discussed in detail in the following sections and formed the basis for this final report.

A.2 Knowledge Transfer Workshop

A.2.1 General Workshop Information

The final knowledge transfer workshop for this study was held on 29th January 2009 at the Royal Society in London to communicate the findings of this study, as well as to get final feedback on the work to refine the discussions included in this document. The workshop was widely publicised, both directly to stakeholder and media groups, as well as to the general public via the Omega website: the flyer for the workshop is presented in Figure A.2. The workshop attracted 42 registered delegates from a diverse range of stakeholder groups, as outlined in Table A.1.

Main thematic area: *Economics/Science/Technology*
 Cost: £££££

Climate related air traffic management

Background

Improved Air Traffic Management (ATM) has a major influence on the trajectories flown by aircraft and hence the environmental performance of the overall system. Although safety considerations are always of paramount importance, there is now growing pressure to account for environmental impact in the development of future ATM systems.

ATM techniques can introduce sources of inefficiency into an aircraft's trajectory that can have negative environmental impacts. These include indirect routings; non-optimum cruise altitudes; restricted airspace; congestion; holding and ground delay, all of which can increase fuel burn and emissions relative to unconstrained operations. Therefore, there is an urgent need to understand the relative impact and environmental cost of these various factors in today's systems to inform the development of future ATM system evolutions, such as the Single European Sky ATM Research (SESAR) initiative.

Study aims

The aims of this study are to:

- Characterise the inefficiencies in the current ATM system (both on the ground and in the air) via literature review and flight data analysis.
- Assess the environmental impacts of these inefficiencies in terms of global radiative forcing effects.
- Undertake a critical review of ATM system evolution plans into the future (e.g. to 2030), including airspace and airport considerations.
- Determine environmental impacts of these evolution scenarios.
- Communicate findings and 'best practice' recommendations to stakeholders.

Lead: University of Cambridge
 Duration: 9 months
 Partners: Loughborough, MMU
www.omega.mmu.ac.uk



The study will primarily focus on the European ATM system and intends to make extensive use of actual flight trajectory and airport operations data to help characterise the current system. Stakeholder participation is being encouraged from the outset in order to understand user needs, obtain expert guidance (both in terms of current system operation and likely future scenarios) and to facilitate knowledge transfer of the study findings.

Benefits

Making the ATM system more efficient is a major area of interest for reducing the environmental impacts of aviation because improvements to the system effect all controlled aircraft and can (in theory) be implemented in shorter timescales compared to wholesale aircraft and engine technology turnover. This study provides in-depth insight into ATM's environmental efficiency allowing recommendations of potential improvements for future systems to be made to stakeholders.

This study is also highly complementary to other Omega studies, especially the airspace charging project where aircraft deviations due to airline routing preferences are examined.

Principal investigator: Dr Tom Reynolds
 E-mail: tr25@cam.ac.uk

Omega is funded by HEFCE

Figure A.1: ATM Study Summary Sheet

Workshop on Environmental Impacts of Air Traffic Management

Royal Society, London
 Thursday 29 January 2009, 9am-1pm

Omega* is an academic partnership addressing issues relating to aviation and the environment. With the University of Cambridge and Loughborough University, Omega is hosting a morning workshop on the environmental impacts of Air Traffic Management (ATM).



ATM has a fundamentally important role to play in aviation environmental mitigation because it affects all the commercial aircraft in the sky. ATM techniques required to handle large volumes of traffic often introduce inefficiencies which cause aircraft to fly non-ideal trajectories. Such techniques include indirect routings; sub-optimal cruise altitudes and speeds; avoidance of restricted or congested airspace; and holding in the air or on the ground. There is also anecdotal evidence that some airlines choose to fly longer distances on some routes in order to take advantage of cheaper ATM costs in different airspace regions. All of these techniques can have negative environmental impacts, such as increased fuel burn, emissions and noise.



The workshop will:

- Present key findings from the Cambridge-led 'Climate Related ATM' Omega study to quantify ATM environmental performance.
- Present key findings from the Loughborough-led 'Environmental Effects of Airspace Charging Regimes' Omega study.
- Discuss the implications of the findings for future ATM systems such as the European SESAR and US NextGen initiatives.
- Highlight complementary activities in this area by key ATM stakeholders.

In addition to the Cambridge and Loughborough ATM research team, stakeholder speakers will include CANSO and the FAA.

Please note that during the afternoon of 29 January, Omega is holding a workshop on JETCLIM/Contrails at the same venue. The event is aimed at industry, Government and NGOs.

Registration and programme is available at www.omega.mmu.ac.uk

For further information, contact Dr Tom Reynolds at the University of Cambridge - tr25@cam.ac.uk

www.omega.mmu.ac.uk

* Omega is an academic partnership of nine UK universities and is funded by the Higher Education Funding Council for England. The partnership is managed by a team at Manchester Metropolitan University, Cardiff and Cranfield universities. The other partner universities are Leeds, Loughborough, Oxford, Reading, Sheffield and Southampton. Omega works closely with Government, industry and NGO stakeholders. It aims to provide a one-stop-shop for the latest information on issues relating to aviation and the environment. More information can be found at www.omega.mmu.ac.uk

Figure A.2: ATM Study Workshop Flyer

Table A.1: Workshop Registered Delegates

Title	First name	Family name	Organisation
Ms	Victoria	Waite	Department for Transport
Mr	Bill	Hemmings	European Federation for Transport & Environment
Mr	Bradley	Taylor	NATS
Eur Ing	Anthony	Willenbruch	SBAC (Civil Air Transport Team)
Dr	Chris	Hume	Airbus - UK
Ms	Lisa	Sheridan	Omega
Dr	Paul	Grimley	Loughborough University
Mrs	Karen	Caton	NATS
Mr	Keith	Mans	Royal Aeronautical Society
Mr	Roger	Worth	Department for Transport
Dr	Richard	Mills	The Boeing Company
Dr	Hugh	Somerville	Sustainable Aviation
Mr	Jarlath	Molloy	Imperial College London
Ms	Aimee	Turner	Flight International
Mr	Alex	Goman	Helios
Mr	Simon	Atkinson	Roke
Mr	Mikko	Viinikainen	Finavia
Mr	Sameer	Savani	Aerospace/Defence Knowledge Transfer Network
Mr	Adam	Sprei	Shell Aviation
Ms	Samantha	Sharif	CANSO
Mr	Patrick	Haller	Thomson Airways
Ms	Zoe	Newsam	NATS
Mr.	David	Knorr	FAA
Ms	Cait	Weston	Aviation Environment Federation
Mr.	Richard	Uchrin	AUXO Energy Consulting
Mr	Marek	Kubala	House of Commons Transport Committee
Mr	Colin	Dunn	Department for Transport
Mr	Colin	Dunn	Department for Transport
Mr	Steve	Hammond	NATS
Mr	Sven	Winter	Loughborough University
Dr	Marcus	Koehler	King's College London
Mr	Keith	Richards	ABTA Ltd
Mr	Stuart	Condie	James Aviation Ltd
Mr	Phil	Stollery	Lochard
Mr	James	Walker	CAA
Mr	Ian	Wrathall	CAA
Mr	Colin	Potter	Unite the Union
Mrs	Anna	Mahoney	Strategic Aviation Special Interest Group
Mr	Chris	Gadson	Easy Jet
Ms	Carrie	Harris	NATS
Mr	Martin	Johnson	CAA
Dr	Naresh	Kumar	Rolls Royce




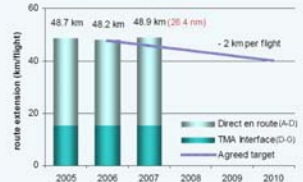
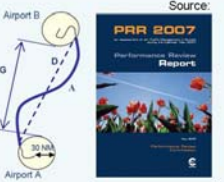
A.2.2 Workshop Agenda

The agenda for the workshop (see Figure A.3) included 45 minute long sessions for each of the two Omega ATM studies (Climate Related ATM that is the focus of this report, and the Airspace Charging study described in a companion Omega report), followed by presentations from three stakeholders summarising their research in complementary areas. The presentation slides for the Climate Related ATM presentation are presented in the next section. A large amount of the workshop time was dedicated to discussions of the presentations, and this is summarised in the final section.

Agenda	
09.15	Omega Climate Related ATM Study Tom Reynolds (Cambridge) & David Gillingwater (Loughborough)
10.00	Omega Airspace Charging Study Lucy Budd (Loughborough) and Tom Reynolds (Cambridge)
10.45	Discussion
11.15	Tea/Coffee
11.30	Stakeholder presentations <ul style="list-style-type: none"> • "The CANSO Global Environment Efficiency Goals for 2050" Samantha Sharif (CANSO, Director Industry Affairs) • "Preliminary Estimation of US ATM Improvement Pools" David Knorr (FAA, ATO Liaison to DFS & CANSO Global Benchmarking) • "NATS Path to 10% Reductions in ATM CO2 Emissions" Carrie Harris (NATS, Head of ATM Environment)
12.30	Discussion
13.00	Lunch, Adjourn

Figure A.3: Workshop Agenda

A.2.3 Presentation Slides

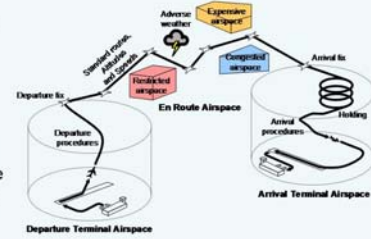
<p style="text-align: center;">Omega Study #25</p> <p style="text-align: center;">Climate Related Air Traffic Management (ATM)</p> <p style="text-align: center;">Dr Tom Reynolds (Cambridge) Dr Lucy Budd, Dr Bob Caves & Dr David Gillingwater (Loughborough)</p> <p style="text-align: center;">Final Briefing – 29 January 2009 – Royal Society, London, UK</p> <p style="text-align: center;"><small>Purchase: Manchester University / Cranfield University / University of Cambridge / University of Oxford University of Sheffield / University of Leeds / University of Reading / University of Southampton / Loughborough University</small></p> <p style="text-align: center;">www.omega.mmu.ac.uk  Aviation in a Sustainable World</p>	<p style="text-align: center;">Motivation</p> <ul style="list-style-type: none"> • ATM has important role in reducing environmental impacts of aviation: ATM affects ALL aircraft • Increasing efforts to quantify ATM's current impact <div style="text-align: center;">  </div> <ul style="list-style-type: none"> • Omega study designed to complement these activities <p style="text-align: center;"><small>Purchase: Manchester University / Cranfield University / University of Cambridge / University of Oxford University of Sheffield / University of Leeds / University of Reading / University of Southampton / Loughborough University</small></p> <p style="text-align: center;">www.omega.mmu.ac.uk  Aviation in a Sustainable World</p>
<p style="text-align: center;">"Flight Inefficiency"</p> <ul style="list-style-type: none"> • Concept commonly used as ATM performance indicator <ul style="list-style-type: none"> □ Quantify difference between "ideal" and "actual" performance □ Focus has been on average route extension over great circle <div style="text-align: center;"> <p>Flight inefficiency metric:</p> $\frac{\text{Actual} - \text{Optimal}}{\text{Optimal}} \times 100\%$ </div> <div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">  </div> <div style="text-align: center;">  </div> </div> <p style="text-align: center;"><small>Source: PRR 2007 Performance Review Report</small></p> <p style="text-align: center;"><small>© University of Cambridge/Loughborough University</small></p>	<p style="text-align: center;">Study Questions</p> <ul style="list-style-type: none"> □ What are current inefficiencies in European ATM? □ What are the environmental impacts of those inefficiencies? □ What is an achievable level of emission savings with future ATM? Which inefficiencies may not be capable of being resolved? □ What are the barriers to change? <p style="text-align: center;"><small>© University of Cambridge/Loughborough University</small></p>

Study Methodology

1. Identify sources of inefficiency in different flight phases
2. Analyse flight data to quantify relative importance of each source
3. Determine environmental implications of inefficiencies identified
4. Interpret results in context of priorities for future European ATM
5. Discussion of findings in light of "Study Questions"

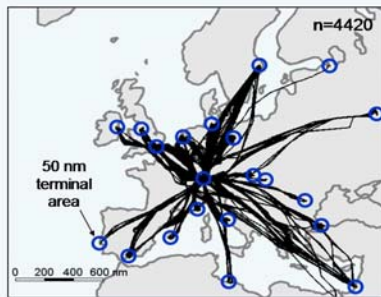
Sources of Flight Inefficiency

- Constraints to aircraft flying their 4D optimal trajectory
 - Lateral track
 - Altitude profile
 - Speed profile

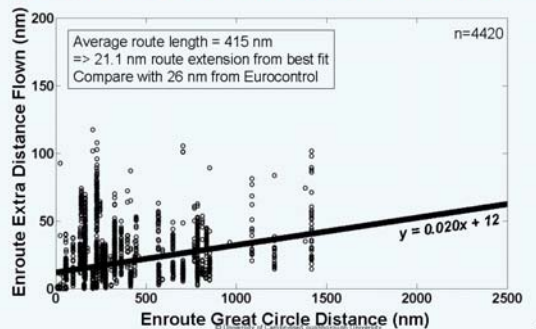


Flight Data Analysis

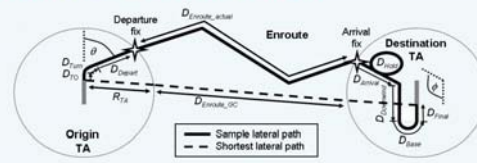
- Flight data recorder info from Swiss during early 2008
- A319, A320, A321 & ARJ 100 aircraft
- 50 nm terminal area radius



Route Extension Results: En Route



Route Extension Model

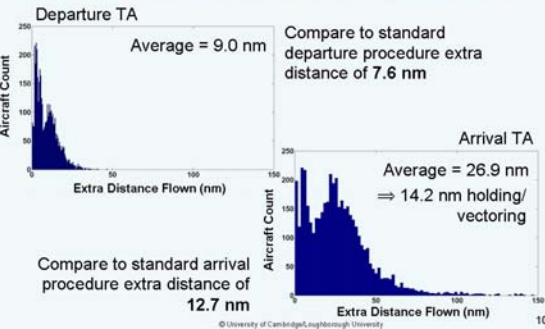


$$XD_{OriginTA} = (D_{TO} + D_{Turn} + D_{Deport}) - R_{TA}$$

$$XD_{Enroute} = D_{Enroute_actual} - D_{Enroute_GC}$$

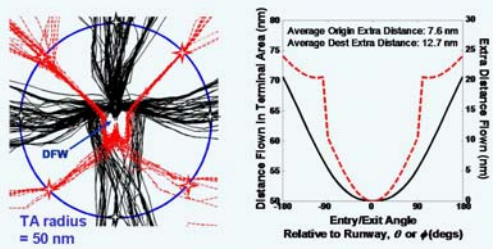
$$XD_{DestTA} = (D_{Arrival} + D_{Hold} + D_{Downwind} + D_{Base} + D_{Final}) - R_{TA}$$

Route Extension Results: Terminals



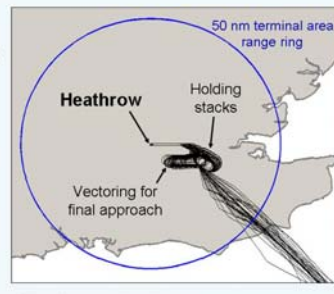
Standard Departure/Arrival Procedures

- Some route extension expected in terminal areas due to standard departure/arrival procedures...

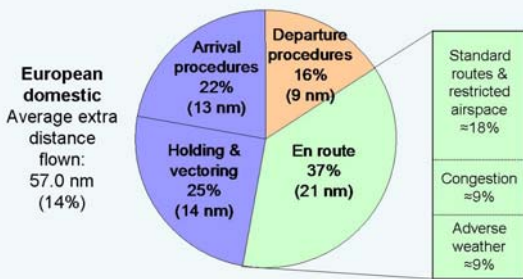


Holding & Vectoring

- ... but a significant amount is due to holding & vectoring
- Holding absorbs delay & maximises runway capacity
- Vectoring for spacing and sequencing on final approach



Track Extension by Flight Phase



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Fuel-Based Inefficiency Metrics

- Track extension is simple and compatible with current surveillance systems, but neglects vertical/speed effects
- Fuel-based metrics compare observed to optimal fuel burn and hence capture these effects and directly relate to emissions (CO₂), but...
- ... are more challenging due to need to determine optimum fuel burn and access to more aircraft info

Professor (Nottingham University) / Cardiff University / University of Cambridge / University of Oxford / University of Sheffield / University of Leeds / University of Reading / University of Southampton / Loughborough University

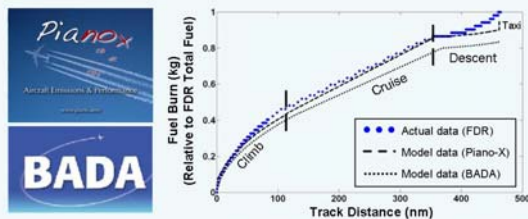
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Omega
Aviation in a Sustainable World

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Aircraft Performance Modelling

- FDR data used to validate candidate aircraft performance models to determine optimum fuel burn



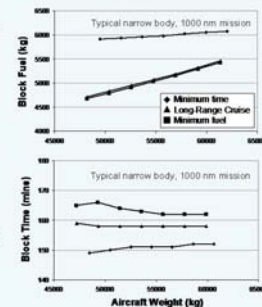
- Piano-X can be better tailored to observed operations

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Optimum Fuel Burn Challenges

- Function of many variables:
 - Aircraft type
 - Weight
 - Route length
 - Winds
 - Centre of gravity
 - Temperature
 - Operator "cost index" i.e. ratio of time-related costs to fuel-related costs

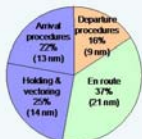


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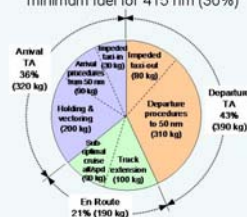
16

Lateral/Fuel-Based Analysis Comparison

Lateral analysis
Average extra distance flown:
57.0 nm over 415 nm (14%)



Fuel analysis**
Average extra fuel burn:
895 kg over 2940 kg Piano-X
minimum fuel for 415 nm (30%)



**DO NOT CITE: these are preliminary results from one route to illustrate the major differences between track extension and fuel burn in the different flight phases. Detailed analysis is on-going

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Study Questions

- What are current inefficiencies in European ATM?
- What are the environmental impacts of those inefficiencies?
- What is an achievable level of emission savings with future ATM? Which inefficiencies may not be capable of being resolved?
- What are the barriers to change?

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Environmental Implications of Inefficiency

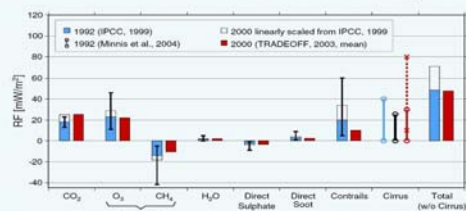
- ATM inefficiencies increase environmental effects
 - Increased track distance flown
 - Contrails
 - Increased total emissions
 - Climate change
 - Local air quality
 - Changed location of emissions
 - Climate change
 - Local air quality
 - Affect ability to accommodate "best practise" techniques
 - Departure: Continuous Climb Departures
 - Cruise: User-Preferred Routings/Altitudes/Speeds
 - Approach: Continuous Descent Approaches, Low Power/Low Drag

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Environmental Implications of Inefficiency

- Findings affect aviation environmental impact predictions
 - IPCC scaling factors of 1.15 on fuel burn, falling to 1.05 in 2015 to account for ATM inefficiencies and their improvement



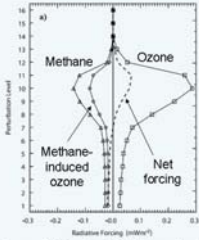
Source: Sausen et al., 2005, "Aviation Radiative Forcing in 2000: An Update on IPCC", Meteorol. Z., 14 (4), pp. 555-561

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Environmental Implications of Inefficiency

- Findings affect aviation environmental impact predictions
 - Location of "non-CO₂" emissions affects climate response



Radiative forcings due to changes in ozone, methane & methane-induced ozone as a function of the altitude of a 5% NO_x perturbation

- Much more work needs to be done: Climate scientists and ATM researchers must collaborate

Source: Köhler et al., 2008, "Impact of Perturbations to Nitrogen Oxide Emissions from Global Aviation", *J. Geophysical Research*, Vol. 113, D11306

Study Questions

- What are current inefficiencies in European ATM?
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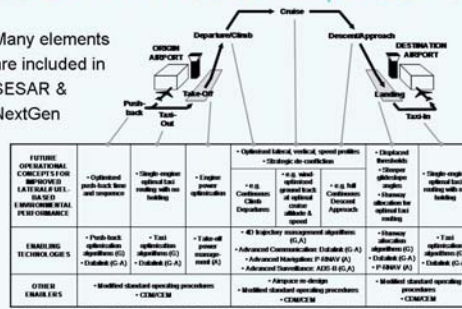
Future ATM Evolution Implications

Inefficiency Source	ATM Improvement Options
Departure procedures	Optimal climb profiles
Standard routes/flight levels/speeds	4D trajectory management for user-preferred trajectories
Restricted airspace	Minimising restricted areas
Adverse weather	Better forecasting/detection
Congested airspace	4D trajectory management
Expensive airspace	ATM charging harmonisation
Arrival holding & vectoring	4D trajectory management
Arrival procedures	Optimal arrival profiles (CDA, LP/LD)

- Major knowns:
 - Pace of ATM infrastructure evolution
 - Relationship between flight inefficiency and congestion

Future ATM Evolution Implications

- Many elements are included in SESAR & NextGen



"Residual" Inefficiencies

- ATM evolution alone cannot address all inefficiencies
- Residual inefficiencies:
 - Separation requirements
 - Avoidance of other aircraft
 - Avoidance of adverse weather
 - Capacity limitations
 - Requirements of other airspace users
 - Environmental trade-offs
 - E.g. need to fly longer route (greater fuel burn) to minimise noise effects

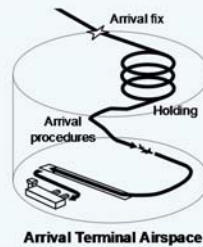
Study Questions

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- What are the barriers to change?

Barriers to an Optimal ATM

- Advanced technology development
- Advanced procedure development
 - E.g. to take full advantage of advanced technologies
- Political will
 - E.g. removing fragmented airspace along national boundaries
- Requirements of other airspace users
 - E.g. Military, general aviation
- Controller/pilot workload
- Airport infrastructure and capacity...

Runway Capacity Relationship



- Holding identified as a major cause of flight inefficiency
- More detailed assessment of European airport capacity conducted to help determine role in future

Airport Capacity Assessment: Challenges

- In Europe, major airports required to declare capacity as part of slot scheduling, air traffic flow management (ATFM) regulation and airport coordination process
- No generally accepted definition of 'declared capacity' and no standard methodology for setting it. (De Neufville & Odoni 2003)
- Methods for declaring capacities therefore vary
- There is no independent audit of these self-declared capacities and in many cases little supporting evidence to verify the veracity of the calculations

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Airport Capacity Assessment: Method

- Major constraint on capacity:
 - Airport layout and geometry (number, direction and length of runways) (De Neufville & Odoni 2003)
- Airport capacity can be estimated using a variety of methods based on arrival & departure capacities
- FAA airport capacity handbook (AC 150/5060-5) and quoted by Horonjoff & McKelvey (1994)

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Airport Capacity Assessment: Method

- Our estimates based on 'daytime hourly capacities' using available data, expert judgment and informed guesswork
- Based on guidance and charts from Federal Aviation Administration (FAA 1983; Horonjoff & McKelvey 1994)
- Charts cover a variety of runway configurations and fleet mixes for both VFR and IFR operations for balanced arrivals and departures for non-segregated operations on all runways (i.e. each runway accepting landings and takeoffs in the same hour)
- IFR operations with a fleet mix of 80% light jets and 20% heavy jets have been taken as the norm for this part of the study

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Airport Capacity Assessment: Method

- FAA handbook-based capacity estimates checked against achieved capacities at 'best-in-class' airports for given runway configurations:
 - London Gatwick for single runways
 - Frankfurt for close parallel runways (making allowance for the additional open V runway) and
 - London Heathrow for more widely spaced parallel runways (operating in segregated mode)
- These airports are known for optimising their taxiways and runway exits, and for the use of High Intensity Runway Operations (HIRO)

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Airport Capacity Assessment: Method

- Three capacity estimates calculated:
 - A realistic estimate - to compare with declared capacity;
 - A minimum likely estimate; and
 - A potential estimate - intended to reflect use of best practice in design of taxiways and exits, together with maximum use of HIRO while respecting known noise abatement preferences
- Each set relates to daytime operations and constraints.
- Estimates will be generally correct to within 5 ATM/hour
- **'Health warning'**: There are many caveats which must be taken into account when interpreting these estimates!

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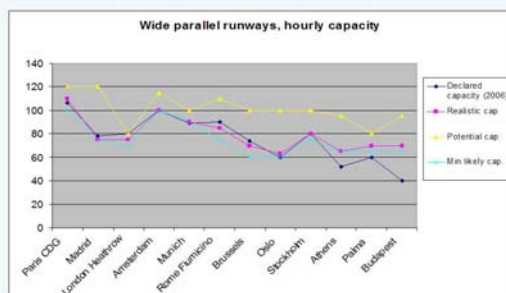
Airport Capacity Assessment: Method

- Many caveats could be lifted or clarified in discussion with the respective airport operations managers and/or the senior air traffic controllers, thus improving the confidence in the estimates
- Further improvements would require extensive data collection and model-building.
- Four types of airport runway configurations have been analysed:
 - widely spaced parallel runways (12 in data set);
 - close parallel runways (9 in data set);
 - multiple non-parallel runways (9 in data set); and
 - single runways (5 in data set).

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Airport Capacity Assessment: Sample Results

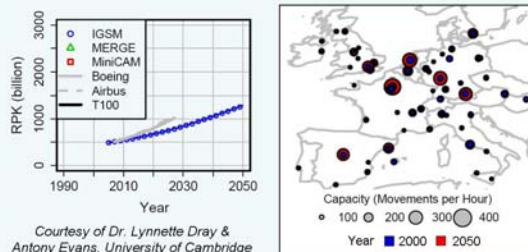


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Future European Airport Capacity Needs

- Current European airport capacity data entered into UCam Aviation Integrated Modelling (AIM) framework



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Conclusions

- ATM has an important part to play in aviation environmental impact mitigation
- Flight inefficiency metrics effective at quantifying impacts
 - Importance of considering terminal area operations
 - Fundamental differences between track extension & fuel burn
- ATM evolution can reduce many inefficiencies but not all
- Reduction potential depends on pace of technology, effects of congestion, barriers to change
- **Continued importance of collaboration**

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A.2.4 Summary of Workshop Discussions

The Omega study presentations were well received. The strong parallels between the Omega work and the stakeholder presentations highlighted the timeliness of the Omega study and its relevance to the stakeholder community. However, there were some differences too, and these stimulated a great deal of discussion. In order to preserve anonymity of the individual delegates raising questions and comments, this section presents a summary of the key discussion items only.

Flight Inefficiency Metrics

The importance of ATM to the reduction of environmental impacts of aviation was universally agreed, as was the use of flight inefficiency metrics to quantify ATM environmental performance. But there was clearly a range of metrics, methodologies and data being used by different stakeholders engaged in inefficiency analysis. There was wide agreement on some of the key messages from this Omega study in terms of need to consider terminal areas and that fuel-based metrics provided additional value which offset their additional complexity, but at present different analysis approaches are preventing valuable comparisons between the activities of the different groups. This is becoming a real concern to some regulators given a European-wide requirement to set ATM performance targets in the near future.

Data Access

Access to operational data is a major challenge for the academic community, while fundamental research resources are often limited in industry. A discussion around this topic suggested that better sharing of data and analysis resources between these groups (with appropriate safeguards, for example with respect to data confidentiality) would be a fruitful area for further activity.

ATM Responsibilities

The difficulty in assigning responsibility for some of the flight inefficiencies was stressed by some delegates. A large number of stakeholders interface with ATM and incentivising behaviours which are in the best interest of the

system as a whole is a challenge, but critical to removing some of the inefficiencies in the future.

Environmental Trade-offs

It was noted that the aviation community needs to agree on how to strike a balance between the spectrum of environmental impacts (climate change, air quality, noise, etc.) rather than focussing on one environmental metric in isolation. It was suggested that case studies that looked at a few specific examples where one environmental impacts may need to be traded with another (e.g. flying longer distances and hence burning more fuel to minimise number of people exposed to a given noise level) would be very useful. The importance of tranquillity (e.g. limiting noise exposure in places such as national parks) also needs careful consideration.

Importance of Collaboration

There was widespread agreement that continued collaboration between the stakeholders was of paramount importance, and the availability of an independent venue for discussion, as provided by Omega, was invaluable.

These main discussion items were used to refine the text and key findings in this final report, demonstrating the importance of the workshop in the knowledge transfer to and from stakeholders which is at the centre of Omega's mission.