

Analysis of Lateral Flight Inefficiency in Global Air Traffic Management

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Making the Air Traffic Management (ATM) system more efficient is a significant area of interest for reducing the environmental impact of aviation. ATM inefficiencies can be present for a number of reasons, including airspace structure (e.g. standard routes and flight levels); airspace restrictions (e.g. military training areas); conflict avoidance (e.g. to keep aircraft separated from each other and adverse weather); and airspace congestion. More efficient ATM that reduces some of these constraints would allow aircraft to fly closer to their optimal trajectories and hence lower the fuel burn and associated emissions of any given flight. In order to analyse these effects, this paper develops inefficiency metrics that quantify how far from the shortest lateral trajectory aircraft currently fly. These metrics are developed for different flight phases and geographic regions by using operational flight data to determine the levels and sources of inefficiency. This study links into the wider Aviation Integrated Modelling project that will permit policy options targeted on the environmental impact of air transportation (such as ATM evolution strategies) to be analysed in the local and global domains. These findings help inform and prioritise design aspects of ATM evolutions (such as the European SESAR and United States NextGen programmes) that affect environmental performance.

I. Introduction

MAKING the Air Traffic Management (ATM) system more efficient is a significant area of interest for reducing the environmental impact of aviation because it allows aircraft to fly closer to their optimal trajectories, thereby lowering fuel burn and associated emissions. Although airframe and engine technological enhancements offer greater 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 (theoretically) be implemented in much shorter timescales and then have immediate impact on *all* the aircraft being managed. Therefore, ATM issues have an important role in environmental impact mitigation.

The widely-cited Intergovernmental Panel on Climate Change (IPCC) report on aviation and the global atmosphere estimated (in 1999) that improvements in ATM could help to improve overall fuel inefficiency by 6-12%¹. There have also been other studies that examined flight inefficiency, primarily focusing on the US^{2,3} and European^{3,4,5} regions. For example, Eurocontrol publish system inefficiency measures each year in the form of average route extension per flight. Although these studies are a useful starting point, they are highly aggregated so it is not possible to determine what is causing the inefficiency. They also have limited geographic scope and use different methodologies. Hence there is a need for additional analysis to provide more detail on sources of inefficiency and allowing a harmonized global perspective on the current state of the global ATM system.

In order to quantify the potential environmental impacts that changes to ATM may have, it is necessary to determine a relevant metric that can be calculated for the current ATM system in different parts of the world, as well as future evolutions. This paper uses the concept of inefficiency metrics to quantify how far from their optimal trajectory aircraft are flying in different flight phases and regions. By identifying the levels and sources of inefficiency observable in the current system, it is possible to determine how much scope exists for improvement through future ATM system evolution, and what elements of ATM system design should be prioritized to minimize environmental impacts.

The wider context for this study in terms of its importance to aviation and environment policy analysis is provided in the next section. Flight inefficiency theory and a discussion of the sources of inefficiency are presented

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next. Inefficiency metrics based on analysis of operational flight data in different parts of the world are presented in Section IV. A discussion of the implications of the global flight inefficiency analysis for current and future ATM system design is given in Section V. Finally, the conclusions from this study are presented in Section VI.

II. Relevance of ATM Inefficiency to Assessment of Environmental Impacts of Aviation

This study contributes to a wide-ranging research project called the Aviation Integrated Modelling (AIM) project⁶ which has the goal of developing a policy assessment tool for aviation, environment and economic interactions. Policies involving air traffic management can only be assessed when their impacts are viewed within the context of the wider air transportation system. Hence the AIM study is developing a set of interacting modules that allow these system-wide impacts to be examined, as shown in Figure 1.

The flight inefficiency characteristics are embedded within the Aircraft Movement Module as shown. This module takes a traffic schedule from an Airport Activity module (which accounts for current and future airport capacity and delay, as well as routing and scheduling impacts) based on predictions from an Air Transport Demand Module (which predicts true origin-ultimate destination passenger and freight demand on a global basis into the future). The required flight schedule is combined with emissions characteristics of current and likely future aircraft technologies available within the forecast horizon as output by the Aircraft Technology and Cost Module. This enables the Aircraft Movement Module to identify the location of emissions released from aircraft in flight while accounting for the inefficiencies introduced by the air traffic control system which is the focus of this study. These emissions are then output to a Global Climate Module in order to examine their climate impacts, while outputs from the Airport Activity and Air Transport Demand Modules go to complementary impact assessment modules for air quality/noise and economic effects. The integrated set of the modules provide a framework for assessing interdependencies and trade-offs between different policy options that may be appropriate for striking a balance between economic benefits and environmental impact mitigation. ATM evolution is one such policy option that can be investigated which primarily impacts the Aircraft Movement module through the flight inefficiency component, and hence motivates the current study.

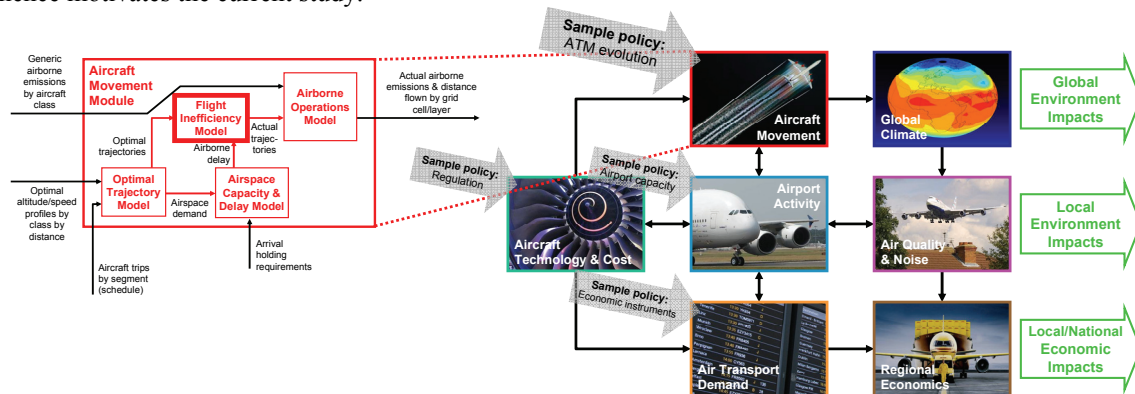


Figure 1: Environmental Analysis of ATM Effects

III. Flight Inefficiency Theory

For the purposes of this study, flight inefficiency is defined as anything that causes an aircraft to fly a path different to its 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. On take off, inefficiencies can be introduced by the 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 non-optimal climb profiles and/or a longer flight path 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 and aircraft often fly around regions of restricted, congested or more expensive airspace, as well as adverse weather. 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.

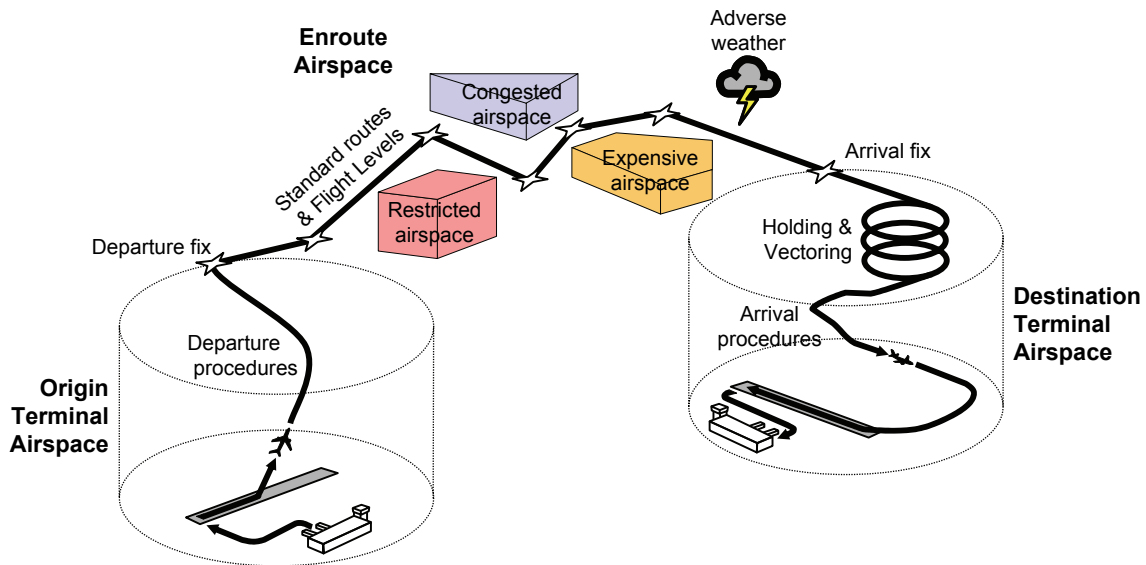


Figure 2: Potential Causes of Flight Inefficiency

A combination of these factors 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 behavior of a flight can be measured in absolute terms (e.g. extra 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 inefficiency can be quantified for a flight along various dimensions using different definitions of the “actual” and “optimal” parameters, as illustrated in Table 1.

Table 1: Sample Inefficiency Parameters

Dimension	Sample “Actual”	Sample “Optimal”
Lateral	Total ground distance	Total great circle distance
	Enroute ground distance	Enroute great circle distance
	Enroute air distance	Enroute “wind-optimised” distance
	Terminal area ground distance	Terminal area “straight-out/in” distance
Vertical	Average enroute altitude	Optimal enroute altitude
Time	Actual block time	Optimal block time
Fuel	Actual block fuel	Optimal block fuel

In the lateral axis, the “actual” ground track distance over the entire flight (or just the enroute or terminal area portion) can be compared to the “optimal” great circle (shortest ground) or wind-optimised (shortest air[†]) distances. Similarly, metrics can be defined on the vertical, time and fuel performance of any given flight. Although these latter metrics are more relevant to environmental analysis, they are considerably more complicated than the lateral case because the optimal performance depends on the characteristics of individual aircraft types. Inefficiencies in the various dimensions can also be inter-related (e.g. lateral inefficiency causes extra flight distance and hence higher fuel burn), while others may not be (e.g. the ground track of a flight could be a great circle and hence the lateral

[†] Consideration of the air distance is relevant in order to distinguish flights that take a longer ground track in order to pick up beneficial tail winds or avoid detrimental head winds (generally only relevant in the enroute flight phase), but this requires access to wind field information which is often not available in flight data.

inefficiency could be zero while time and fuel inefficiency are non-zero if the vertical and speed profiles are sub-optimal). This paper uses lateral inefficiency based on great circle “optimal” distances due to its ease of definition for all trajectories and aircraft types, and to allow comparison with results published by Eurocontrol and FAA. Distinctions are made between the origin terminal area, enroute and destination terminal area flight phases in order to identify the relative importance of each region given the inefficiency characteristics are quite different in each case, as illustrated in Figure 3.

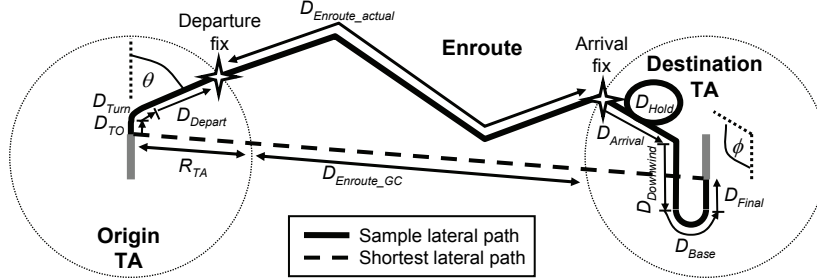


Figure 3: Terminal Area and Enroute Lateral Inefficiencies

Lateral inefficiency of the form of extra distance (XD) flown beyond the great circle (GC) distance in the origin terminal area ($OrigTA$), enroute and destination terminal area ($DestTA$) is represented by:

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

$$XD_{Enroute} = D_{Enroute_actual} - D_{Enroute_GC} = IM_{Lateral} \cdot D_{Enroute_GC} \quad (3)$$

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

In the origin terminal area, the extra distance flown is the sum of the take-off “straight-ahead” distance (D_{TO}), the distance in the turn towards the departure fix (D_{Turn} : a function of the angular difference between the runway orientation and the departure fix, shown as θ in Figure 3) and the straight distance to that fix (D_{Depart}), compared to the terminal area radius (R_{TA}). The enroute lateral inefficiency shown in (3) is most naturally shown by the lateral inefficiency % metric as a function of the enroute distance, and this is the form of the results to be presented in the next sections. Extra distance in the destination area is a more complex function of the distance from the arrival fix to the start of the approach procedure ($D_{Arrival}$), any required holding/vectoring distance (D_{Hold}) and the approach distance. The approach procedure adopted depends on the angle of arrival into the terminal area relative to the destination runway angle (shown as ϕ in Figure 3): it is assumed that if $|\phi| > 90^\circ$ then a “downwind” leg is flown ($D_{Downwind}$) followed by a “base” leg (D_{Base}) and the final approach (D_{FA}), and if $|\phi| \leq 90^\circ$ then the downwind segment is eliminated and an appropriate proportion of the base leg is flown (ranging from a full semi-circular base leg when $|\phi| = 90^\circ$ and no base leg when $|\phi| = 0^\circ$). A model of these terminal area behaviors is shown in Figure 4.

The top left panel shows actual arrival and departure tracks for one day (from ETMS data: see next section) into Dallas Fort Worth Airport (DFW). The arrival and departure fixes are clearly evident at about 50 nm from the airport, and hence this is taken to be the terminal area radius in this paper. Realistic estimates for the various components of the procedures required in Eqns. 2 and 4 can be obtained, as shown in the top right panel, which can then be used to develop a simple model of the theoretical paths flown in a generic terminal area with any entry/exit path angles, as shown in the bottom left panel. This simple model can then be used to determine the theoretical distance flown in the origin and destination terminal areas as a function of the entry/exit angles (assuming zero holding and vectoring distance), and this is shown in the bottom right panel. Assuming random terminal area entry/exit angles (i.e. uniform random distribution of θ and ϕ) the average extra distance flown in an origin terminal area is calculated to be 7.6 nm, while in the destination terminal area it is calculated to be 12.7 nm, i.e. an additional 5 nm on average is expected in the destination terminal area, primarily due to the longer final approach path (D_{FA}) compared to the straight-ahead take-off distance (D_{TO}). These average values of extra distance flown in the terminal areas due to standard departure and arrival procedures quantify two of the inefficiency sources identified in Figure 2.

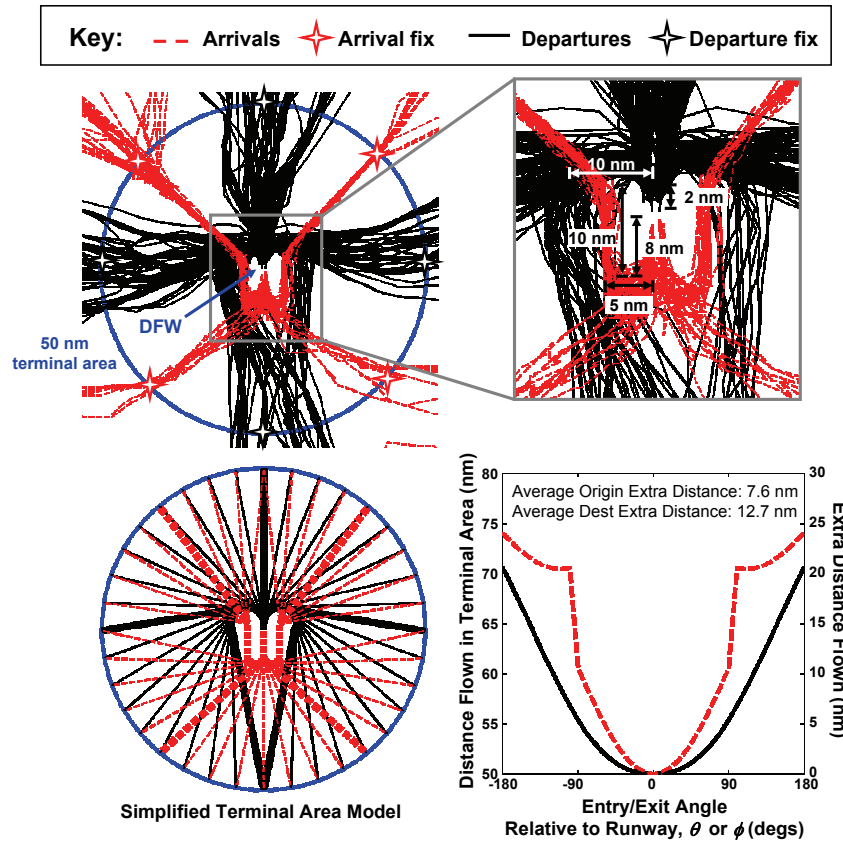


Figure 4: Terminal Area Extra Distance Behaviours

The next sections use the lateral inefficiency formulations discussed above for the enroute and terminal area to analyse operational flight data in different world regions. The terminal area model values will be used in these analyses to determine the relative importance of terminal area to enroute inefficiencies, and to identify the importance of holding and vectoring as inefficiency sources in the terminal areas when the observed average extra distance being flown are greater than the theoretical minimum average values identified above. The sources of inefficiency in the enroute phase will be discussed through comparison of inefficiency results from different days.

IV. Global Lateral Inefficiency Analysis

A. Methodology

Lateral inefficiencies were calculated using the basic definitions discussed above using actual flight data to allow a direct comparison of results between different flight phases and geographic regions. The sources of flight data were the Enhanced Traffic Management System (ETMS) for domestic US flights, airline Flight Data Recorder (FDR) archives for internal European flights, and MOZAIC[‡] data for other world regions. The ETMS data was based on FAA radar track archives from a 4 week period in 2005 covering all commercial traffic over the US (with some minimal filtering to remove potentially sensitive information). The FDR data was from a random sample of flights during early 2008 over the European network of a large international airline. The MOZAIC data was based on in-flight measurements taken during revenue service from 1995 to 2006 from five Airbus A340 aircraft of several European and African-based airlines taking part in a European Union-sponsored atmospheric observation campaign. Latitude and longitude (amongst many other) states are available from all sources with at least 60 second update rates, permitting a detailed lateral flight inefficiency analysis to be conducted within and between some important world regions. The following sections present and compare results from *intracontinental* flights within US, Europe and Africa, and *intercontinental* oceanic and non-oceanic flights.

[‡] MOZAIC = Measurements of OZone and water vapour by in-service Airbus airCRAFT, <http://mozaic.aero.obs-mip.fr>

B. Intracontinental Flights: USA, Europe & African Regions

Results from analysis of the intracontinental flights within the USA, Europe and African regions are given in Figure 5 below.

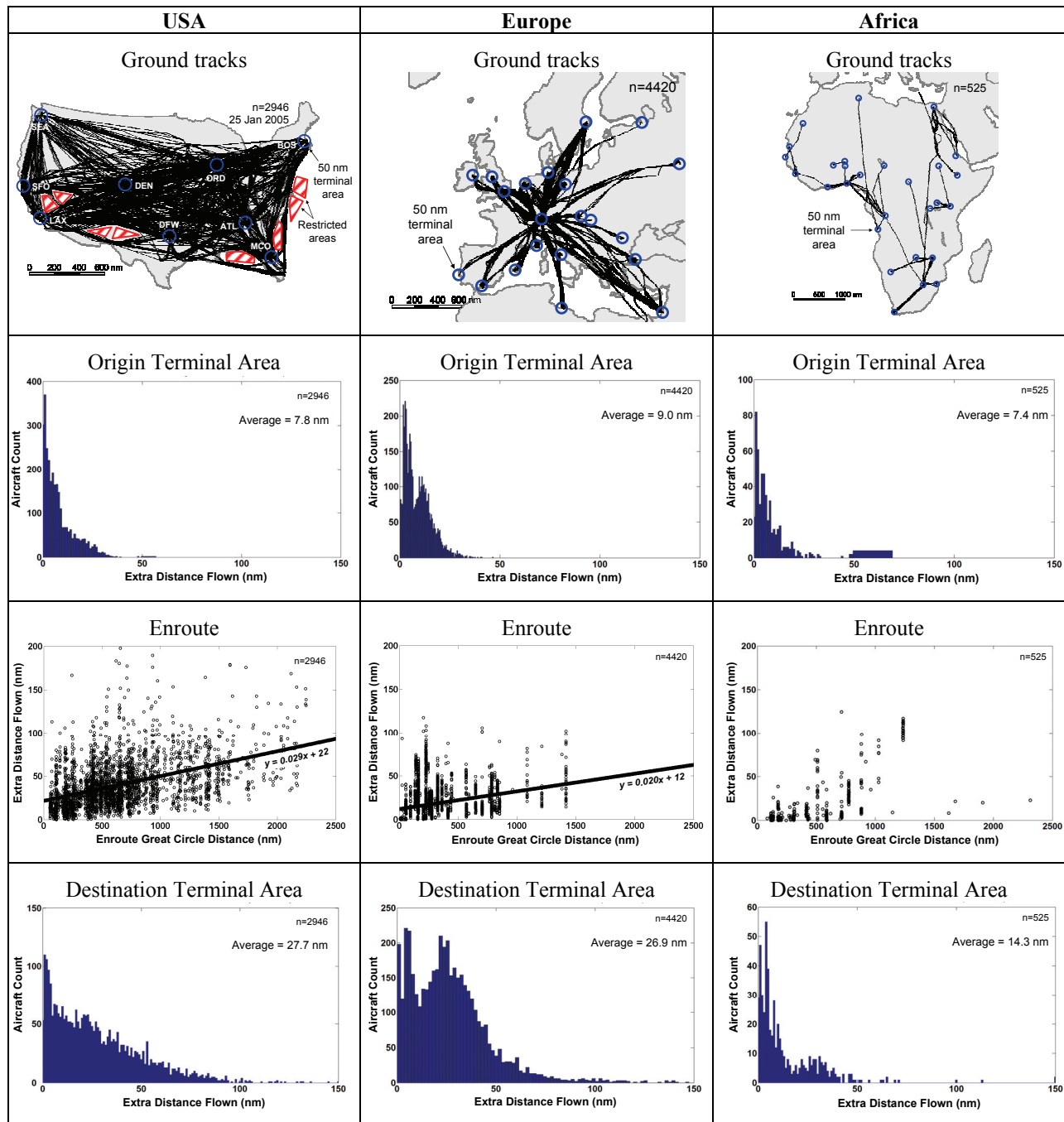


Figure 5: Inefficiency Results for Intracontinental Flights

The US ground tracks illustrate approximately 3000 flights departing from 9 major airports[§] (but landing at any destination) covering the whole of the country on 25 January 2005 (an “average” day with no major adverse weather within the system). These tracks immediately highlight the importance of restricted airspace. The airway structure is

[§] Boston (BOS), Atlanta (ATL), Orlando (MCO), Dallas (DFW), Chicago (ORD), Denver (DEN), Seattle (SEA), San Francisco (SFO) and Los Angeles (LAX).

tailored to the avoidance of these regions and hence is a major driver of the inefficiency results (especially enroute inefficiency, discussed later). The observed average extra distance flown in the origin terminal area was 7.8 nm, very close to the 7.6 nm theoretical average from the simple model presented in the previous section. Given the flight track data covers a large number of airport pairs in the US, the assumption of a uniform random distribution of terminal area exit angles in the simple model is reasonable, and hence these results suggest the observed extra distance flown in the terminal area is almost exclusively down to standard terminal departure procedures. The results of enroute extra distance flown illustrate interesting behavior: most exhibited less than 100 nm of extra en route flight, although there is significant variability. A linear best fit to the data suggests a “constant (22 nm) plus percentage (2.9%)” relationship between extra enroute flight distance and route length. The average route length in the data was 635 nm, where the best fit line implies an extra enroute flight distance of 40.4 nm. By contrast to the origin terminal area, the average extra distance flown in the destination terminal area observed in the data was 27.7 nm compared to a theoretical average for standard arrival procedures (with no holding or vectoring) of 12.7 nm. This suggests that an average of 15 nm of holding and vectoring per flight is observed in the data (with a small number of flights having 100 nm or more of extra flown distance in the destination terminal area). These results indicate that the total extra distance flown on the “average” (635 nm) US flight was observed to be 75.9 nm (12% of route distance). The relative proportions of lateral inefficiency between the originTA:enroute:destinationTA regions were 10%:53%:37% for that average flight.

The middle column gives the European results based on the FDR data. Because this data is based on the European network of a single carrier, the geographic coverage and route diversification is more limited than the US data.^{**} Despite this, the enroute extra distance flown characteristics are similar in form to the US results, with values again generally less than 100 nm and a best fit line defined by a slightly smaller constant (12 nm) and slope (2.0%). The distributions of extra distance flown in the origin and destination terminals area are subtly different to those in the US, with a skewing towards specific values. This is most likely due to the smaller number of airport pairs in this dataset such that the specific terminal area entry/exit angles of these routes are evident in the distribution, compared to the more even distribution in the US data. The average value of the destination terminal area extra distance was 26.9 nm (similar to the US) showing there was a considerable amount of terminal area vectoring and holding in Europe too, consistent with the high system demand in the two regions. The average flight distance in Europe was 415 nm, implying a total extra distance for the average flight being 57.0 nm (14% of route distance). This is similar to the US value of 12%. The contribution to the total extra distance from enroute flight was 21.2 nm, which can be compared directly to the 26.0 nm in the published Eurocontrol metrics: the difference is attributable to the limited number of city-pairs in the dataset. The relative proportions of lateral inefficiency between the originTA:enroute:destinationTA regions were 16%:37%:47% for the average flight. These results show that a greater proportion of the extra distance was flown in the destination terminal area in Europe compared to the US because the average route was shorter. In addition, studies that just consider the enroute portion (as is commonly the case) could be missing over 60% of the extra distance being flown by a typical flight.

The results from the African continent are based on a much smaller sample size (and hence there is no best fit to the enroute results) but show similar patterns of behavior in enroute and terminal area inefficiencies. The African ATM infrastructure is more basic than in the US and European regions, characterized by a small number of ground-based navigational aids, minimal radar coverage and basic procedural separation over much of the continent leading to airport capacities as low as 6 aircraft per hour at some international airports⁷. However, the traffic levels in Africa are an order of magnitude lower than in the US and European regions and hence these reduced demands can be accommodated at levels of inefficiency equivalent to those in the much more developed regions. Note that the average extra distance in the destination terminal area is only 1.6 nm larger than the theoretical minimum from the model, reinforcing that the low traffic levels at the African airports in the dataset are leading to negligible need for vectoring and holding. However, it is unlikely that these low levels of inefficiency could be maintained if traffic levels increased significantly unless accompanied by infrastructure improvements. The relationships between inefficiency, airport and airspace capacity is an area of major future research.

The US flight data also provides an opportunity to examine the impact of some specific sources of inefficiency previously discussed for the enroute phase, namely traffic (and hence congestion) level and adverse weather. Because the ETMS data was chosen from specific dates, it allows the effects of these issues to be accounted for through careful selection of data for comparison. Figure 6 shows a comparison of the average enroute extra distance flown from two different days when the traffic levels differed by around 10% in the 9 analysis airports analysis (typical of the traffic difference expected between a low and high traffic day, e.g. Saturday compared to Friday). A consistently higher average extra distance flown of 10-30 nm and higher variability is associated with the higher

^{**} The routes analysed were all flown by Airbus A319, A320 and A321 aircraft on the scheduled service of the airline concerned.

demand levels, suggesting this is a typical general effect of more congested airspace, although this is an area where much more research is required.

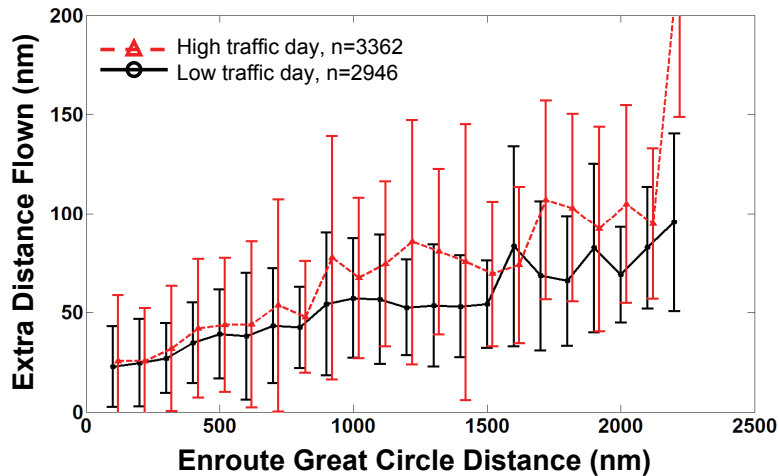


Figure 6: Enroute Lateral Inefficiency Impacts of Traffic Level

Figure 7 shows a comparison of the enroute lateral inefficiency for flights between Florida and Texas (primarily MCO and DFW) on a “normal” day (25 January 2005) and the day of maximum impact of Hurricane Katrina (29 August 2005). The 29 August ground tracks are clearly displaced far north of their normal 25 January location to avoid the hurricane region and this causes a significant increase in the enroute lateral inefficiency for these flights by a factor of 3 to 4. Despite the unusually large size of the adverse weather region in this case, these increased inefficiency impacts are localized to the immediate surrounding region and causes only negligible effect on the wider system.

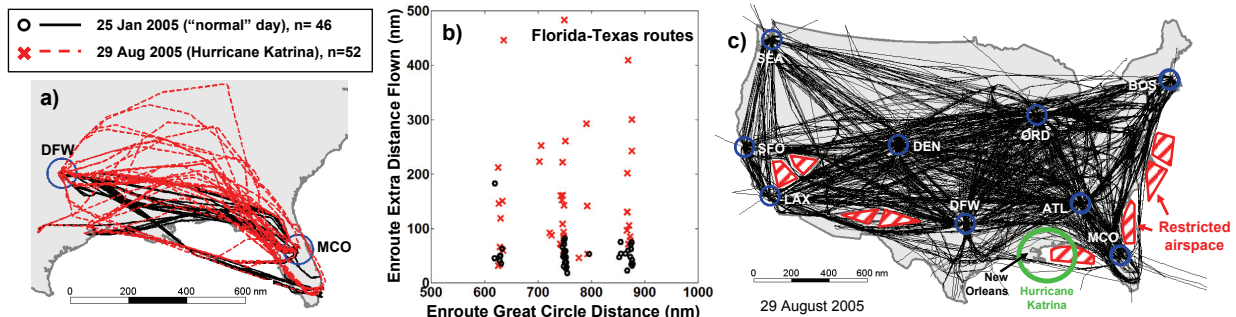


Figure 7: Enroute Lateral Inefficiency Impacts of Adverse Weather

C. Intercontinental Flights: Europe-US (Oceanic) & Europe-Asia (Non-Oceanic)

The ground tracks for flights from western Europe to eastern US regions (and hence predominantly over the North Atlantic region) are shown in Figure 8. Because the oceanic airspace is largely out of radar surveillance and VHF radio communication coverage, flights in this region typically still rely on procedural separation rules based upon a system of prescribed North Atlantic Tracks (NATs). These tracks are defined by a set of waypoints along the 10° longitude lines which are joined together in different ways every 24 hours in an attempt to capture favorable tailwinds from the jet stream on eastbound flights and avoid adverse headwinds on westbound flights. The resulting limited number of ways of joining adjacent waypoints to form the NATs leads to the characteristic “diamond” pattern observable in the ground tracks over the oceanic airspace. The greater track flexibility available in the radar airspace over Europe and USA is clearly evident upstream and downstream of the oceanic region. The extra enroute track distance in these oceanic flights is slightly greater as a result of the rigid track structure, with the best fit line having parameters slightly greater than the intracontinental results described earlier. Although the oceanic airspace could be made more efficient by increasing routing flexibility (e.g. enabled by advanced communication, navigation and surveillance systems), the observed inefficiency results are somewhat misleading because they suffer from a limitation of the simple lateral inefficiency definition employed in this study. The NATs are specifically designed to

account for the location of the jet stream winds, i.e. minimize “air distance” rather than “ground distance” and this can only be accounted for in the analysis by assessing the wind field for each flight, a considerably more complicated proposition. This will be explored in subsequent studies.

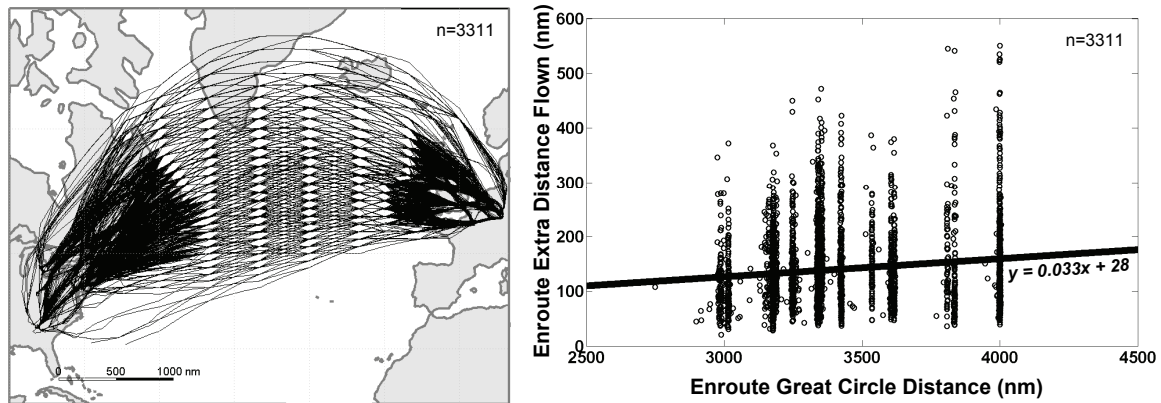


Figure 8: North Atlantic Lateral Inefficiency

Intercontinental flights that do not involve oceanic segments are presented in Figure 9 for flights from Europe to Asia. Note that these tracks involve nearly 2500 flights and yet are concentrated into a relatively small number of major flows from central Europe eastwards. This can be attributed to the small number of international jet routes available in these regions, coupled to the large areas of restricted airspace (especially over China and Russia), political factors, strict overflight rules and inhospitable terrain. This concentration into a small number of flows leads to relatively high lateral inefficiencies, with extra track distances of up to 1200 nm being observed, with major adverse environmental and economic consequences due to the extra fuel burn.

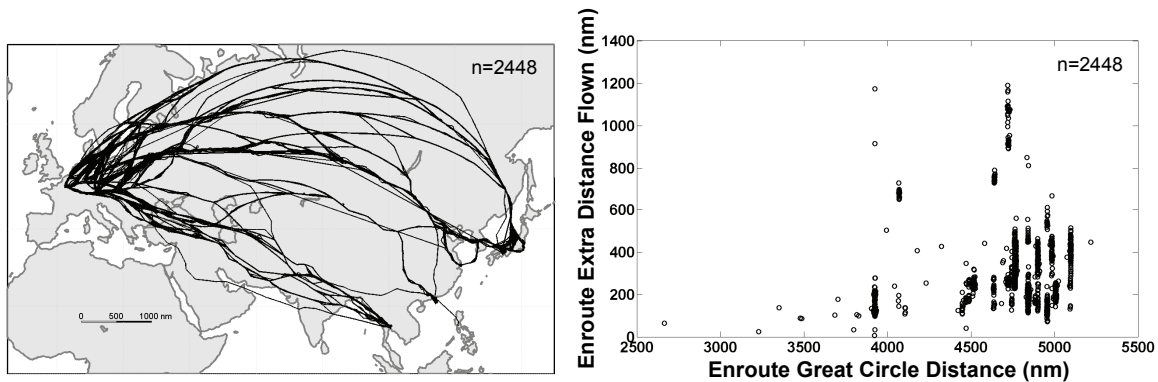


Figure 9: Europe to Asia Lateral Inefficiency

V. Consequences for Future ATM System Evolution

The findings from the previous section are summarized in Figure 10. This shows typical values from the US and European analysis of the contribution to the extra track distance flown from the various sources of inefficiency identified in Figure 2, along with their potential mitigation in future ATM system evolutions.

The biggest contributor (at 27%) was standard routes and restricted airspace, which were combined due to the fact that standard routes were observed to accommodate many airspace restrictions. 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. These would improve efficiency in both the enroute and oceanic airspace. These regions also currently suffer from Communication, Navigation and Surveillance (CNS) limitations 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 eliminating the need for a rigid oceanic track structure. Traffic is

growing more rapidly in some other parts of the world where the current infrastructure is unlikely to be able to accommodate it. 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 other parts of the world where growth has been more gradual. The outlying inefficiency results observed in the Europe to Asia flights highlight the adverse effect of large areas of restricted airspace which, in long distance flights, can lead to significant extra distance being flown. Increasing the number of available airways with the ultimate goal of wholesale removal of these large restricted areas would therefore be highly beneficial, but this may be a political rather than technical challenge.

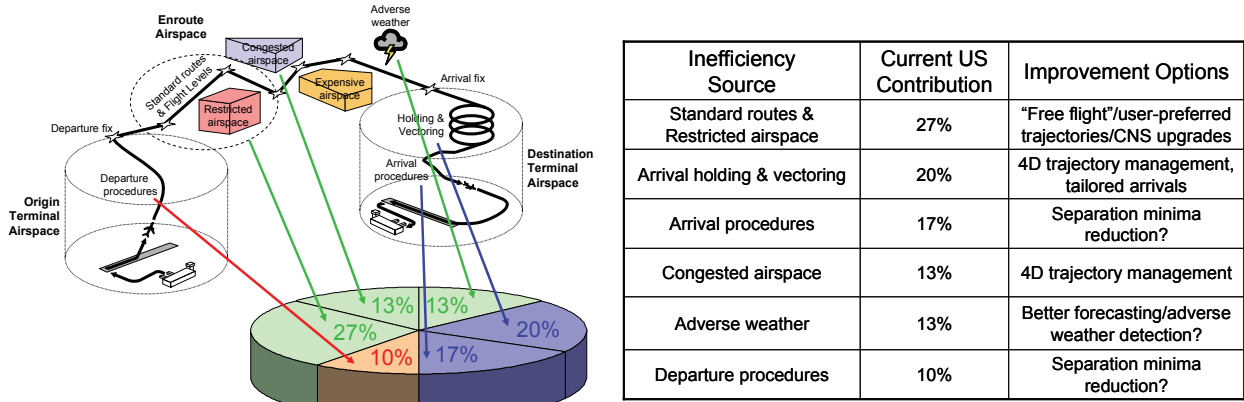


Figure 10: Inefficiency Sources and Their Potential Mitigation

At present a relatively small proportion of traffic is affected by these major airspace limitations (see Figure 11): about 2% of worldwide seats are scheduled between regions 2 and 3 in both directions. However, intra-Asian traffic accounted for 19% of worldwide seats in 2005 (and growing) and it is unclear whether these regions of restricted airspace also affect these flights. If so, their consequences could be much more profound.

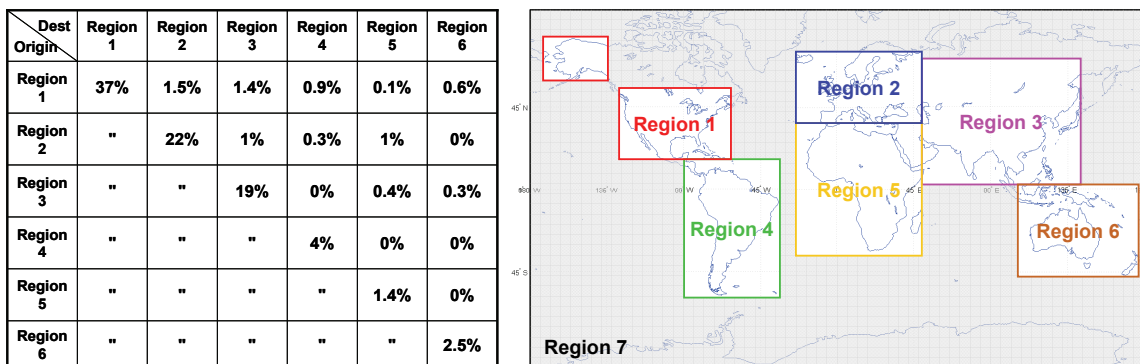


Figure 11: Seat Distribution Within/Between World Regions [based on 2005 OAG scheduled flights⁸]

The second most important inefficiency source (at 20%) was observed to be arrival holding and vectoring. Future concepts that involve 4-dimensional trajectory management, and tailored arrivals in particular, should greatly reduce the need for holding and vectoring within the destination terminal area. It would enable delays to be determined far in advance of an aircraft's arrival into the terminal area, allowing a more efficient accommodation of demand. 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. Elements of 4-dimensional trajectory management are already deployed in parts of the US, but major efficiency gains could be achieved by system-wide application.

Standard arrival procedures (excluding holding and vectoring) were the next biggest inefficiency source (at 17%). The need for alignment of the flight path with the limited set of runway orientation available at any airport implies there will always be some excess track distance observed in this phase. However, relaxation of constraints

imposed on standard arrival procedure design (such as stabilization criteria and/or separation minima) could help to minimize this contributor to inefficiency.

Congested airspace was observed to contribute around 13% to the extra track distance in the US data. This, too, should be helped by 4-dimensional trajectory management. However, as previously highlighted, 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. Adverse weather was observed to contribute another 13% of extra track distance flown in the US: better forecasting and adverse weather detection to allow adverse weather to be avoided more efficiently should be possible in the future. Finally, departure procedures were observed to contribute 10% of the average extra track distance. The same issues described above in relation to arrival procedures also apply in this case.

The seat distributions shown in Figure 11 also reinforce the dominant role that ATM in US and Europe (regions 1 and 2) still play, accounting for over 60% of worldwide seats within and between these regions. Major ATM improvement programmes are underway (NextGen in the US⁹, SESAR in Europe¹⁰), both of which have efficiency improvement objectives as part of their environmental impact reduction goals, largely driven by opportunities consistent with those identified in Figure 10 and discussed above.

VI. Conclusions

Air traffic management has an important part to play in reducing the environmental impacts of aviation. This paper has demonstrated how inefficiency metrics are an effective way of quantifying the scope for improvement within the ATM system in the various flight phases and geographic regions, and the insights that can be gained from their use. Key findings from a simple lateral form of inefficiency metric include the importance of terminal area operations (where approximately 50% of the US and European extra track distance is incurred), the relative impact of different sources of inefficiency in each flight phase and the possible ways of improving efficiency in future ATM evolutions. Future studies will use more sophisticated forms of inefficiency metrics, such as fuel-based forms which account for inefficiencies in all the control dimensions (lateral, vertical, speed and time) to produce outputs that are more easily interpreted from an environmental impact perspective, especially when integrated into the wider AIM policy assessment framework.

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