

Development of Flight Inefficiency Metrics for Environmental Performance Assessment of ATM

Tom G. Reynolds

Institute for Aviation and the Environment, University of Cambridge
Cambridge, United Kingdom

Abstract—Air traffic management has a fundamentally important role in reducing the environmental impacts of air transportation by reducing the inefficiencies in the paths flown by aircraft. The potential causes of flight inefficiency are discussed in this paper, followed by the development of flight inefficiency metrics based on lateral track extension and fuel burn to quantify the environmental performance of the system. These metrics are used with flight data to illustrate their utility. Lateral flight inefficiency metrics are found to be easy to compute and compatible with current surveillance technologies, but they do not allow some important environmental performance characteristics to be captured. Fuel-based metrics are found to be far more effective in this regard, but suffer from significantly greater complexity in their implementation. The implications of the analyses for future ATM evolution strategies are discussed to show the insights that can be gained from this type of analysis.

Keywords—flight inefficiency metrics; environmental impacts; air traffic management.

I. 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 (such as the need to keep aircraft safely separated) 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.

The increasing attention being focused on 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) [1] and the similar program underway between US and Europe called the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) [2]. In the initial phase of Aspire, three 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. 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 [3]. 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” [4]. The major ATM modernization initiatives in Europe (Single European Sky ATM Research (SESAR) [5]) and the US (Next Generation Air Transportation System (NextGen) [6]) 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.

In order to better understand the environmental impacts of ATM now and in the future, one approach being adopted by ATM providers is to quantify their performance using relevant flight inefficiency metrics. Section II of this paper discusses causes of flight inefficiency, followed by a description of flight inefficiency metrics that quantify how far from their optimal trajectory aircraft are flying in different flight phases in Section III. Two different forms of inefficiency metric based on lateral ground track extension and excess fuel usage are developed and used with appropriate flight data to illustrate their utility in Sections IV and V respectively. By identifying the levels and sources of inefficiency observable in the current system using these two metrics, 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: this is discussed in Section VI and then conclusions in Section VII.

II. 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 optimum four-dimensional trajectory (i.e. latitude/longitude ground track, vertical profile and speed profile). Flight inefficiency has different potential causes in the different flight phases, as illustrated in Figure 1 and described in the following sub-sections.

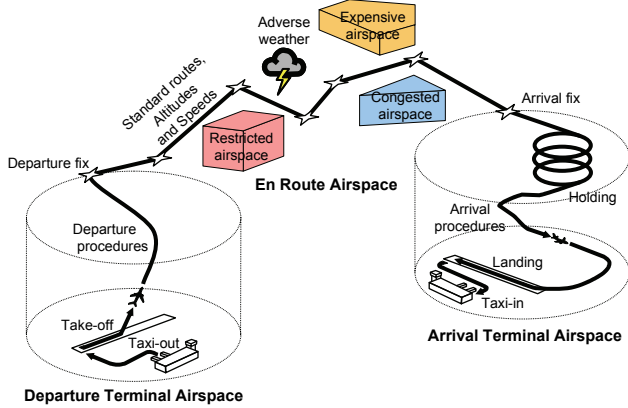


Figure 1: Potential Causes of Flight Inefficiency

A. Departure Terminal Airspace

Inefficiencies can first affect a flight during taxi-out to the runway (e.g. being given a long taxi route or one with many stops and starts caused by congestion or runway crossings) and at the take-off procedure itself (e.g. requiring 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. The orientation of the departure runway relative to the ultimate direction of flight is another key factor. 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 2.

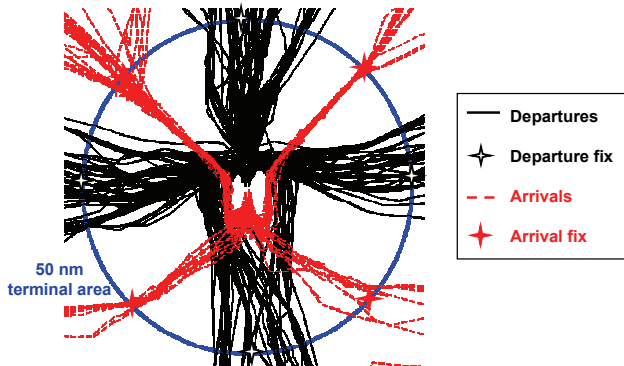


Figure 2: Ground Track Extension due to Standard Departure/Arrival Procedures at Dallas Fort Worth Airport (ETMS data, from [7])

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 its ideal trajectory.

B. 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 [8] (in low traffic conditions the standard lateral routing requirement may be relaxed). The standard routing 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. Ground tracks for all the flights originating from 10 major US airports on one day in 2005 are presented in Figure 3. Several of the en route inefficiency sources are evident: standard routes cause the concentration of flights into a 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).

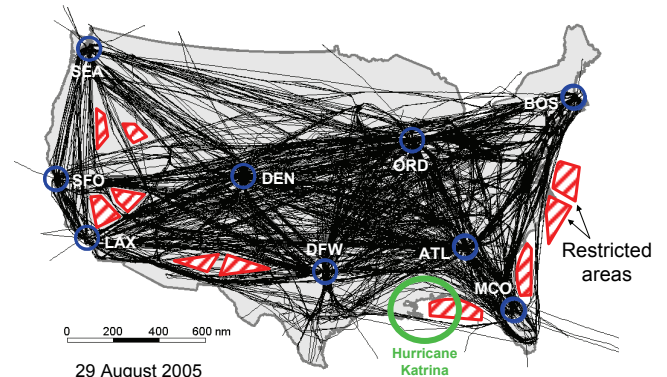


Figure 3: Ground Track Extension due to En Route Airspace Inefficiency (ETMS data, from [7])

There is also some evidence [9] that differences in en route charging regimes in a given area may lead to total cost savings for longer routes 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. In Figure 4 the different colours represent different charging rates in the Eurocontrol regions. Significant differences between charging rates in neighbouring airspace regions can be observed and this can make it possible for longer routings (which hence burn more fuel and produce higher emissions) to be cheaper in terms of ATM+fuel costs for the airlines in some city pairs, 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 Section IV.

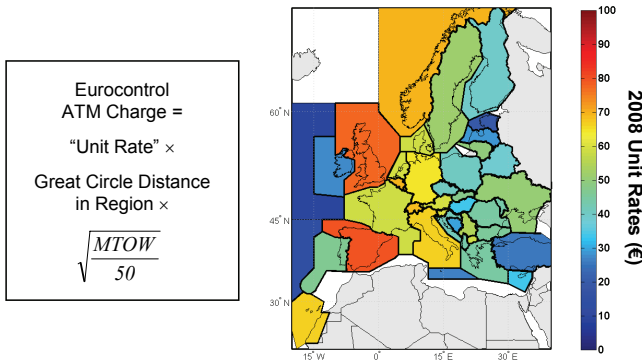


Figure 4: Eurocontrol Airspace Charging Rate Differences by Region

C. 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 illustrated in Figure 2. 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 followed by a long taxi route.

III. 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 behavior 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:

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

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

The lateral ground track extension inefficiency metric based on the difference between the radar ground track and great circle distance is commonly used by the air navigation service providers due to its ease of calculation and interpretation [10][11], 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 trajectory near to a great circle lateral track is flown) may have relatively poor fuel (and hence environmental) performance due to sub-optimal altitude and speed profiles

which are not captured at all by this metric. In addition, the great circle distance is not necessarily the shortest ion the presence of winds.

TABLE 1: SAMPLE INEFFICIENCY PARAMETERS BY FLIGHT DIMENSION

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) Minimum ground distance simple to calculate 	<ul style="list-style-type: none"> Difference between actual and minimum ground track distance is not always proportional to environmental impact (e.g. no vertical/speed elements) Great circle distance is not shortest in presence of wind
	Flown air distance	Minimum air distance	<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 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. aircraft weight, winds)
Speed (also surrogate for Time)	Average en route speed (block time)	Optimal en route speed (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)

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 and hence their value is limited relative to the complexity of their implementation. Although fuel-based inefficiency metrics (where the actual fuel burn is compared to the optimal fuel burn) suffer from implementation complexity 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, as well as other species which are directly proportional to fuel burn such as SO_x and water.

The sections that follow present inefficiency analyses using the lateral ground track extension and fuel-based metrics in order to illustrate their application and utility. A variety of sources of flight data are used, including:

- Flight Data Recorder (FDR) archives from a random sample of Swiss Airlines A320-family flights within Europe during early 2008.
- Enhanced Traffic Management System (ETMS) FAA radar track archives from a known 4 week period in 2005 covering all commercial traffic over the US (with some minimal filtering).
- MOZAIC* data taken from revenue flights from five Airbus A340 aircraft serving mostly international routes covering much of the globe from 1995 to 2006.

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

IV. LATERAL INEFFICIENCY ANALYSIS

This section summarizes and expands upon the lateral flight inefficiency analysis described in detail in [7] where the ground tracks of a large number of flights from the different data sources 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.

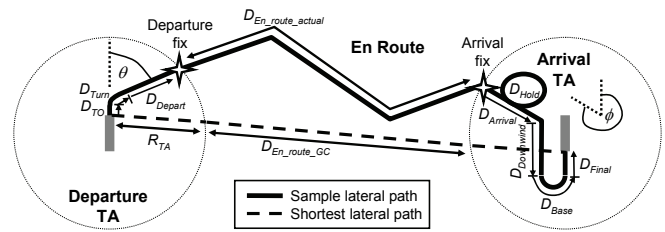


Figure 5: Terminal Area and En Route Ground Track Extension Definitions

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 key findings from this analysis for flights within and between different world regions are presented in full in [7] and summarized in Table 2.

TABLE 2: TOTAL GROUND TRACK EXTENSION RESULTS

Flight region	Av. route length in data (nm)	Average TGTE (nm)	Average TGTE (%)	Flight data source
Europe domestic	415 nm	57 nm	14%	FDR (n=4420)
US domestic	635 nm	76 nm	12%	ETMS (n=2946)
Africa domestic	489 nm	41 nm	8%	Mozaic (n=525)
North Atlantic	3430 nm	176 nm	5%	Mozaic (n=3311)
Europe-SE Asia (typical)	4705 nm	316 nm	7%	Mozaic (n=2448)
Europe-SE Asia (extreme)	4730 nm	1100 nm	23%	Mozaic (n=37)

Flights entirely within the European and US regions exhibit similar average total ground track extension (TGTE) inefficiency metric characteristics: the average route in the European data was observed to be 14% (57 nm) longer than the great circle trajectory, compared to 12% (76 nm) for the US. A lower value of 8% (41 nm) was observed in the data for African flights: although the ATC system is relatively under-developed in this region, the low traffic levels and the small number of markets in the region mean that the major airways can provide relatively direct routes. North Atlantic flights exhibited approximately 5% ground track extension, although in absolute terms this equated to over 170 nm (much larger than in continental flights) which can be almost entirely attributed to the relatively rigid North Atlantic Track airway structure. Note, however, that these tracks are designed to be wind-optimized, so the air track extension (as compared to the ground track extension) may be much less.

* Measurements of OZone and water vapour by in-service Airbus airCRAFT, see <http://mozaic.aero.obs-mip.fr>

Similarly, the 7% (316 nm) total ground track extension observed in the Europe to Asia flights can be attributed to the large regions of restricted airspace over parts of Russia and China, leading to relatively few available international airways for flights between these regions. In the extreme case, some routes from Europe to parts of SE Asia were observed to regularly exhibit total ground track extensions of over 20% (1100 nm), but these are believed to be due to geo-political issues (e.g. over-flight restrictions imposed on some airlines).

The total ground track extension is broken down into the different flight phases for the European, US and African domestic regions in Figure 6, assuming circular departure and arrival terminal areas with radius of 50 nm.

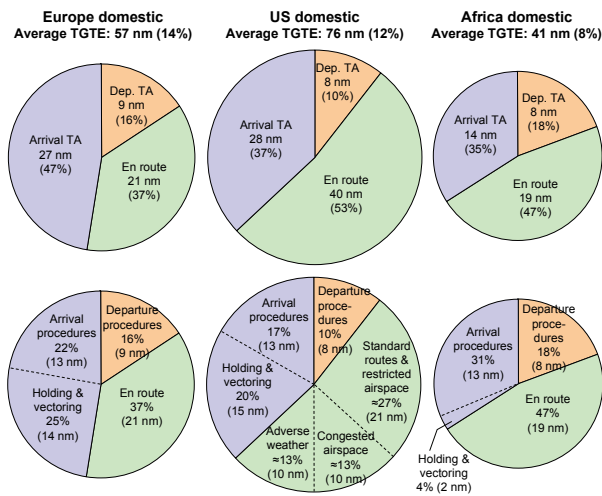


Figure 6: Regional Ground Track Extension Results Breakdown By Flight Phase (top) and By Inefficiency Factor (bottom)

The relative sizes of the pie charts represent the relative differences in the total ground track extension. The top row of results present the aggregate results of the regional ground track extension by flight phase and highlight the importance of considering the inefficiencies in the en route *and* terminal areas. The bottom row provides a breakdown by flight inefficiency factors identified in Figure 1 when possible through further analysis of flight data. It is apparent that the departure procedures account for approximately 8 nm of ground track extension (10-18% of the TGTE depending on the region). A simple model of departure procedures presented in [7] determined that, with a random distribution of the terminal area exit angle relative to the runway orientation (denoted as θ in Figure 5), the expected average track extension is 7.6 nm. Hence, the observed track extension in all three regions 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.

By contrast, the standard *arrival* procedures (coming in over an arrival fix and then aligning with the arrival runway orientation, an angular change denoted as ϕ in Figure 5) modeled in a similar way in [7] suggests an expected track extension of 12.7 nm and hence only account for about half

the ground track extension in the arrival terminal area in the Europe and US data. The balance can be attributed to the need to hold and vector traffic to account for the high traffic levels and make maximum use of limited runway resources in these regions. Interestingly, virtually no holding and vectoring was seen in the African data: although typical runway capacities are very low at African airports (capacities of 6 movements/hour are quite common, even at international airports [12]), demand is often even lower such that the observation of minimal holding and vectoring in the data is not a surprise.

The ETMS data used in the US analysis also 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 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 (e.g. convective activity), it was possible to determine the general impact of these inefficiency sources, as described in [7]. 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 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 and this is a major need for additional research. But the observed impacts give pointers to the relative importance of these causes of inefficiency, with the balance being attributed to standard routes and restricted airspace.

There are still a few potential causes of flight inefficiency highlighted in Figure 1 that have not yet been considered: standard altitudes/speeds and expensive airspace. As previously described, a shortcoming of the lateral analysis is that altitude and speed effects are not captured, and hence the effects of standard altitudes/speeds cannot be assessed with this metric. But further analysis of the flight data did make it possible to undertake an assessment of the relative importance of expensive airspace on track extension. As mentioned previously, this is most likely to be an issue in European airspace, where differences in ATM en route charges between neighboring airspace regions can be significant (see Figure 4) 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. To explore the importance of this issue, 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 [13], while fuel costs (and CO₂ production) were determined using fuel burn estimates from Eurocontrol's Base of Aircraft Data (BADA) [14] and average hedged jet fuel prices for 2004, the year for which the flight plan routes applied [from personal communication with D. Gillingwater, Loughborough University, 30 October

2008]. The routes and CO₂ production as a function of ATM+fuel costs for a B757-200 (B752: a typical aircraft used on these routes) are presented in Figure 7.

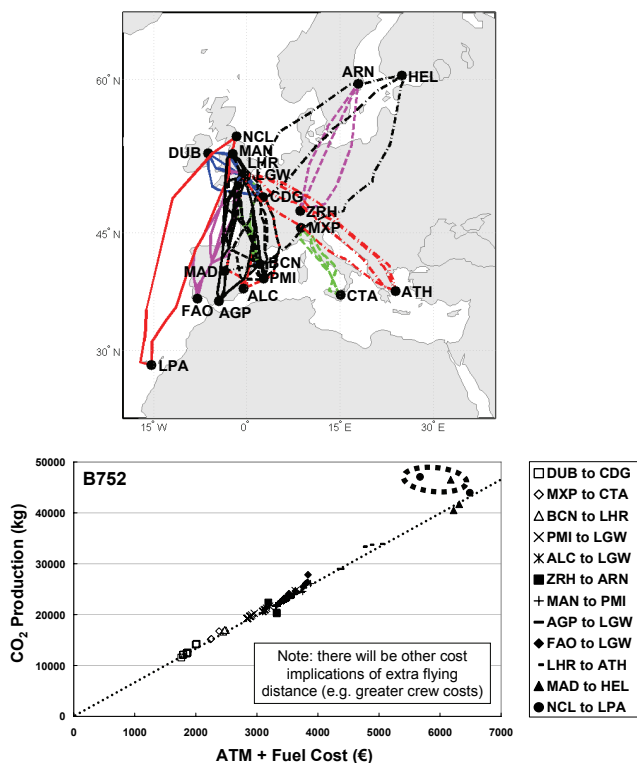


Figure 7: European Airspace Charging Analysis Results

The dotted line in the lower graph represents the general behavior 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 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) lie off this line, which can be interpreted as there being a slight ATM+fuel cost incentive to fly further (Newcastle/Gran Canaria (NCL-LPA) and Madrid/Helsinki (MAD-HEL)). By cross-referencing those routes to the charging areas and rates illustrated in Figure 4, it is seen that this incentive is due to the presence of much lower cost airspace in immediately neighboring airspace compared to the more direct route. For example, the NCL-LPA route goes further west into significantly cheaper oceanic airspace compared to overflying French, Spanish and Portuguese airspace on the direct route. This oceanic routing was 123 nm longer and created 3,100 kg more CO₂ compared to the most direct route, but had €837 less ATM+fuel cost (at 2004 prices). The longer/cheaper MAD-HEL route involved flying around the expensive German airspace which lie on the direct path and into much cheaper Eastern European airspace. 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, but these were not explicitly considered here. This analysis highlights that there are only a few routes where flying longer distances may have any cost incentive, and they generally 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 1 and can be neglected in Europe in all but a few specific cases. The same is expected to be true for the rest of the world.

This section has highlighted that there are significant insights that can be gained from using the most basic form of lateral inefficiency metric, i.e. ground track extension. However, it does not provide any way of determining the relative importance of altitude and speed constraints in terms of environmental impacts. The additional insights that can be gained in this regard from using a fuel-based inefficiency metric, along with the added complications this brings, are discussed in the next section.

V. FUEL INEFFICIENCY ANALYSIS

As previously mentioned, fuel-based inefficiency analysis is more complicated because it requires availability of aircraft states that are currently not routinely surveilled, as well as more detailed modeling 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 available for this study was from Swiss A319/A320/A321 aircraft types serving European destinations, and hence this aircraft family and geographic region will be the focus of this analysis. Note that this part of the study is on-going and will be reported in more detail in future publications

The first challenge in fuel-based analysis is to have access to an appropriate aircraft performance model. Two models were assessed for this analysis: Lissys Ltd's Piano-X [15] and Eurocontrol's BADA (used for the airspace charging analysis described above). Comparison of each model outputs with representative samples of FDR data was conducted: results from one representative flight are given in Figure 8 in terms of fuel burn as a function of distance flown.

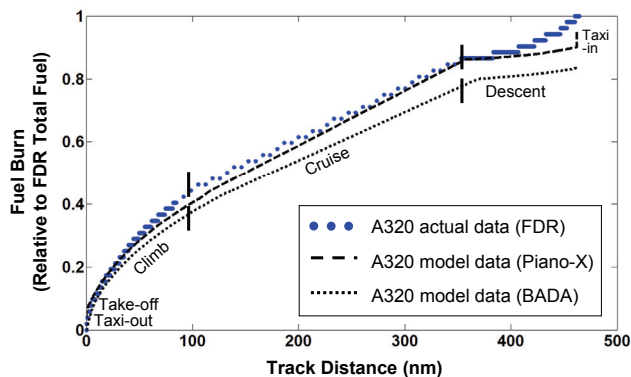


Figure 8: Aircraft Performance Model/FDR Data Comparison

It is apparent from this figure (and was found to be the case generally) 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.

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, optimum fuel also depends on a number of other factors, such as winds, temperature, the aircraft's center of gravity and the operator's "cost index" [16]. This latter element 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 9 for the case of a representative mission for a typical narrow-body aircraft.

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 9 for an example mission to be a compromise between the two extremes in terms of time, but which enables most of the fuel benefit to be achieved.

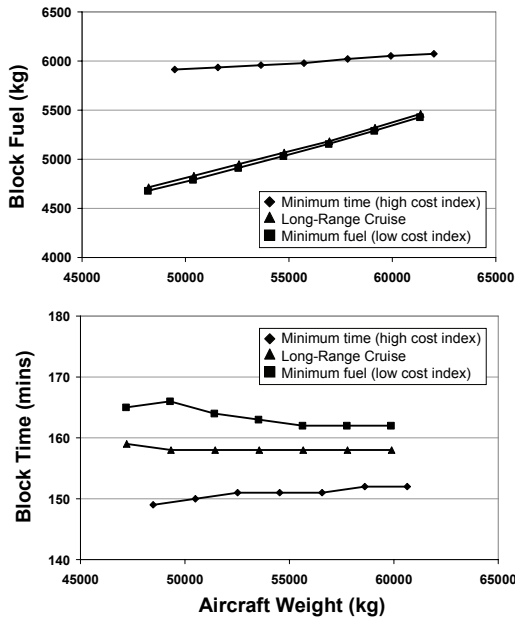


Figure 9: Time/Fuel Prioritization Impacts

It is, therefore, important to account for these factors in a fuel inefficiency analysis when possible. The cost index was not available in the FDR dataset, and hence in this analysis the optimal fuel burn was taken to be the minimum theoretical fuel given by the aircraft performance model (i.e. with the lowest cost index). The fuel inefficiency analysis was conducted with all of the A320 European flights for which FDR data was available (1794 flights in total). Figure 10 presents a surface plot of normalized optimal total fuel burn as a function of aircraft weight and route distance for this aircraft type, and this was compared to the actual fuel burn from the FDR data in the routes analyzed.

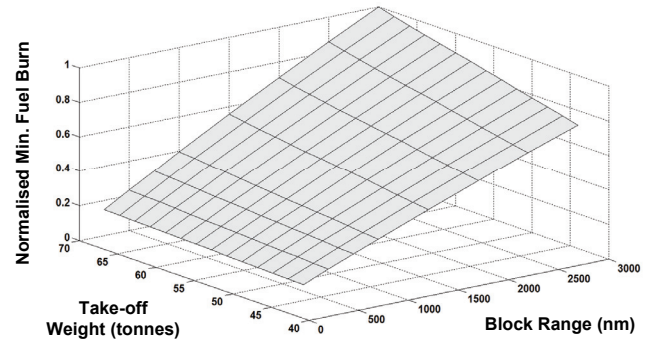


Figure 10: Minimum Fuel Burn as Function of Take-off Weight and Range

Figure 11 presents the lateral and fuel inefficiency results for these flights side-by-side.

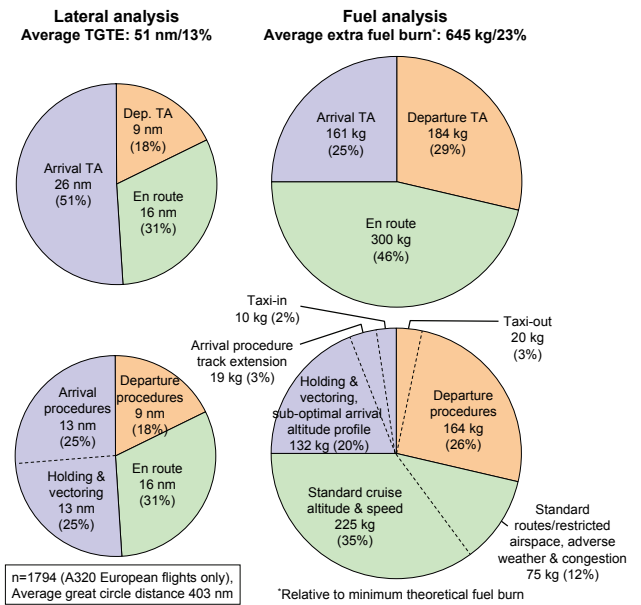


Figure 11: Lateral and Fuel Inefficiency Comparison (European A320s) By Flight Phase (top) and By Inefficiency Factor (bottom)

The lateral inefficiency results for the A320 (13% total ground track extension) are very similar to those from the more complete full European set (14% total ground track extension). It is apparent that the average fuel inefficiency is significantly greater than the equivalent average lateral

inefficiency, with 23% more block fuel[†] being burnt on average relative to the theoretical lowest average fuel burn. Note that the average fuel inefficiency would be slightly lower if a different cost index was used in the aircraft performance model (e.g. representing minimum flight time instead of minimum fuel burn). This issue will be explored in later publications.

In addition to the overall inefficiency levels differences, there are also differences in the relative contribution of each flight phase between the lateral and fuel inefficiency results, with departure terminal area and en route phases having relatively greater contributions, while the departure terminal area plays a relatively smaller contribution.

The departure terminal area contributes 29% of the overall fuel inefficiency compared to only 18% of the lateral inefficiency. This is due to a combination of two factors. Firstly, because the fuel burn rate is high in the initial climb phase (see Figure 8) even the relatively small amount of track extension in that phase leads to disproportionately greater fuel burn. Secondly, the fuel-based metrics include taxi-out fuel, so ground inefficiency is being captured whereas this was not included in the lateral results.

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 a quarter of the observed extra fuel burn is due to en route track extension. The remainder is assumed to be due to inefficiencies in the other dimensions, i.e. sub-optimal cruise altitude and speed which, again, could not be quantified in the lateral inefficiency analysis. Note that the routes analyzed here were relatively short European routes: 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 and this translates to a relatively small excess fuel burn contribution from track extension in the arrival phase. However, engine thrust increases are required to execute the holding patterns identified in the lateral analysis or to accommodate level flight segments in non-Continuous Descent Approach procedures, and these are the cause of the remainder of extra fuel burn in this phase. Taxi-in inefficiency levels are also included in the fuel inefficiency analysis, but this is seen to not have a major effect on the overall fuel inefficiency level contributions in that flight phase.

VI. IMPLICATIONS FOR FUTURE ATM NEEDS

It is important to understand that not all of the inefficiencies identified through the analyses presented above are entirely due to air traffic management. Other factors, such as airline policies and rules imposed by other parties (such as separation requirements), also affect the inefficiencies being observed and some of these “residual

[†] Block fuel includes all the fuel burnt from “blocks off” at the departure gate to “blocks on” at the arrival gate, i.e. covering all the flight phases shown in Figure 1.

inefficiencies” may never be removed entirely. But the findings do give pointers towards appropriate priorities for future ATM designs to reduce flight inefficiency where improvements in technology or procedures could be beneficial.

The biggest cause of inefficiency in both the lateral and fuel analyses was observed to be standard routes, altitudes and speeds. These inefficiencies could be improved through operating paradigms that allow more widespread use of flight away from the rigid airway structure (made up of standardized routes, altitudes and speeds), as proposed in many “free flight” or user-preferred trajectory concepts which are included in 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 en route airspace, allowing more direct routes and flight at user-preferred cruise altitudes and speeds which minimize fuel burn. The current need for airspace structure is also tied to the 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. The high 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.

The next major inefficiency source observed in both the lateral and fuel-based results was arrival holding and vectoring. 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 for ATM to manage arrival delay in a more environmentally-friendly way. Future concepts that involve four-dimensional trajectory management, 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

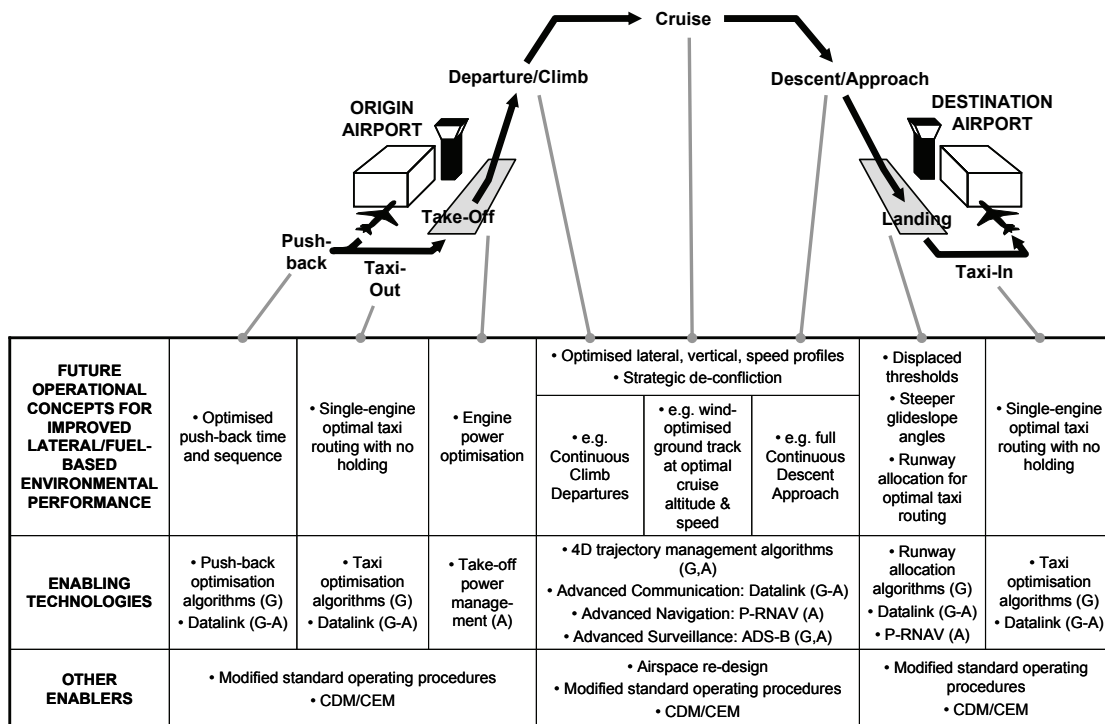
aircraft's arrival into the terminal area, allowing a more efficient accommodation of delay. For example, by slowing the cruise speed of an aircraft by a few knots on a long distance flight to manage its arrival into the terminal area at a pre-determined time when it can be accepted without delay is much more efficient than having aircraft enter the terminal area at an unplanned time, then holding them until a runway slot is available. In addition, it should allow aircraft to fly nearer to their optimal altitude and speed profiles during descent and approach which should help reduce this aspect of fuel inefficiency. Elements of four-dimensional trajectory management are already deployed in parts of the US, but major efficiency gains could be achieved by system-wide application, as is proposed in the European SESAR and US NextGen concepts.

Track extension due to standard arrival procedures (excluding holding and vectoring) was the next biggest lateral inefficiency source, but was less significant in terms of fuel burn as long as the aircraft is at low engine power, which it typically is during descent up until the final approach. By contrast, departure procedures were seen to be much more important in the fuel analysis due to the high fuel burn rates during that flight phase. In both standard departure and arrival procedures, the need for alignment of the flight path with the limited set of runway orientation available at any airport and the need to maintain a minimum separation distance between aircraft to ensure safety implies there will always be some excess track distance or fuel burn observed in these phases. However, careful relaxation of constraints

(such as reduced separation minima and/or stabilization criteria) imposed on standard procedure design without compromising safety could help to minimize these contributors to overall flight inefficiency.

The other factors that have been semi-quantified in this analysis have been inefficiencies due to congestion and adverse weather. Congested airspace related inefficiency should also be helped by the four-dimensional trajectory management previously discussed. 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. The need to avoid regions of adverse weather is likely to continue into the future to maintain passenger comfort and safety. However, better forecasting and adverse weather detection to allow affected regions to be avoided more efficiently should be possible in the future.

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 currently being introduced or developed are summarized in Figure 12. Future plans for ATM integrate many of the improvements suggested above 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% (with the remainder being residual inefficiency with current technologies, policies, etc.).



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 12: Future ATM Concepts Summary

Figure 12 also includes initiatives designed to reduce local environmental impacts of air quality and noise because future ATM systems will need to address these as well. Air quality and noise would be helped through initiatives during the take-off and landing stages of flight that allow aircraft to fly closer to their optimal vertical and speed profiles, e.g. Continuous Climb Departures (CCDs) and Continuous Descent Approaches (CDAs). The objective of a CDA, for example, is to minimize periods of level during the descent and approach phases of flight, thereby keeping aircraft higher and at lower thrust for longer, reducing fuel burn, emissions and noise impacts. Enabling aircraft to do this during the entire descent and approach phases can reduce fuel burn and associated emissions 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.

The major challenge in all of these future ATM concepts will be improving environmental performance in the face of growing demand. 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 likely to increase in the coming decades because traffic growth will exceed the possible efficiency gains (even given aircraft technological improvements). Hence, policy measures such as Emissions Trading Schemes which incorporate aviation in an effective manner will have a major part to play in managing aviation's environmental impacts.

VII. CONCLUSIONS

This paper has identified the importance of quantifying the performance of the ATM system to understand its current and potential future role in environmental impact mitigation of air transportation. ATM inefficiencies are used for this purpose to identify system constraints which cause aircraft to fly away from their optimal four dimensional trajectories. Flight inefficiency metrics have been discussed against a number of flight dimensions, with a lateral ground track extension-based metric being the easiest to implement, and a fuel-based metric being the most meaningful. These two types of metric have been used to analyze flight data and the results illustrate the insights that be gained through a coupled lateral and fuel-based analysis: the former helps interpret the latter, while the fuel-based analysis provides insights into inefficiency areas that cannot be identified through lateral analysis alone. Future work will continue to refine the approaches presented here to better understand the use of flight inefficiency metrics for environmental performance assessment of ATM.

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AUTHOR BIOGRAPHY

Tom G. Reynolds has joint research appointment with MIT's Aeronautics and Astronautics Department and Lincoln Laboratory. This work was conducted while he was a Senior Research Associate at the University of Cambridge Institute for Aviation and the Environment. He has expertise in air transportation systems engineering, with a particular focus on air traffic control strategies for reducing environmental impacts of aviation. He obtained his Ph.D. in Aerospace Systems from the Massachusetts Institute of Technology in 2004.