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Modelling Environmental & Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Project

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The Aviation Integrated Modelling project is developing a policy assessment capability to enable comprehensive analyses of aviation, environment and economic interactions at local and global levels. It contains a set of inter-linked modules of the key elements relevant to this goal. These include models for aircraft/engine technologies, air transport demand, airport activity and airspace operations, all coupled to global climate, local environment and economic impact blocks. A major benefit of the integrated system architecture is the ability to model data flow and feedback between the modules. Policy assessment can be conducted by imposing policy effects on the upstream modules and following implications through the downstream modules to the output metrics, which can then be compared to a baseline case. A case study involving different evolution scenarios of the US air transportation system from 2000 to 2030 is used to show the importance of feedback and to model a sample policy scenario in order to illustrate current capabilities.

I. Introduction

AVIATION has experienced rapid expansion as the world economy has grown. Passenger and freight movements by air continue to increase, making air travel the fastest growing sector amongst all transportation modes. Managing the global air transportation system to ensure continued economic and social benefits, while simultaneously mitigating environmental impacts, is becoming a major challenge. The system is large, complex, multi-disciplinary and involves numerous stakeholders with different agendas. Therefore, sustainable development of the system depends crucially on the delivery to policymakers and stakeholders of robust results incorporating improved understanding of the processes and interactions between the key system elements that determine environmental, societal and economic impacts. There is an urgent need to model the contributions of aviation at local and global levels in order to assess aviation policies to be pursued in the future that strike appropriate balances between these impacts. The Aviation Integrated Modelling (AIM) project[§§] has been established to develop a policy assessment tool relevant to this need. A description of the modelling approach being used in AIM is provided in the next section, followed by a sample case study to illustrate the importance of capturing interactions between its modules and how different policy scenarios can be investigated.

II. Aviation Integrated Modelling Architecture

The AIM project has the goal of developing a policy assessment tool for aviation, environment and economic interactions at local and global levels, now and far into the future. AIM's architecture contains a set of integrated modules of the key elements relevant to this goal, as illustrated in Figure 1. These modules include: (A) an Aircraft Technology & Cost Module to simulate aircraft fuel use, emissions production and ownership/operating costs for various airframe/engine technology evolution scenarios; (B) an Air Transport Demand Module to predict passenger

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and freight flows into the future between origin-destination city pairs within the global air transportation network; (C) an Airport Activity Module to investigate operations within the vicinity of the airport and calculate delays and future airline response to them; (D) an Aircraft Movement Module to simulate airborne trajectories between city-pairs, accounting for airspace inefficiencies and delays for given Air Traffic Control (ATC) scenarios; (E) a Global Climate Module to investigate global environmental impacts of the aircraft movements in terms of multiple emissions species and contrails; (F) a Local Air Quality & Noise Module to investigate local environmental impacts from dispersion of critical air pollutants and noise from landing and take-off (LTO) operations; and (G) a Regional Economics Module to investigate positive and negative economic impacts of aviation in various parts of the world.

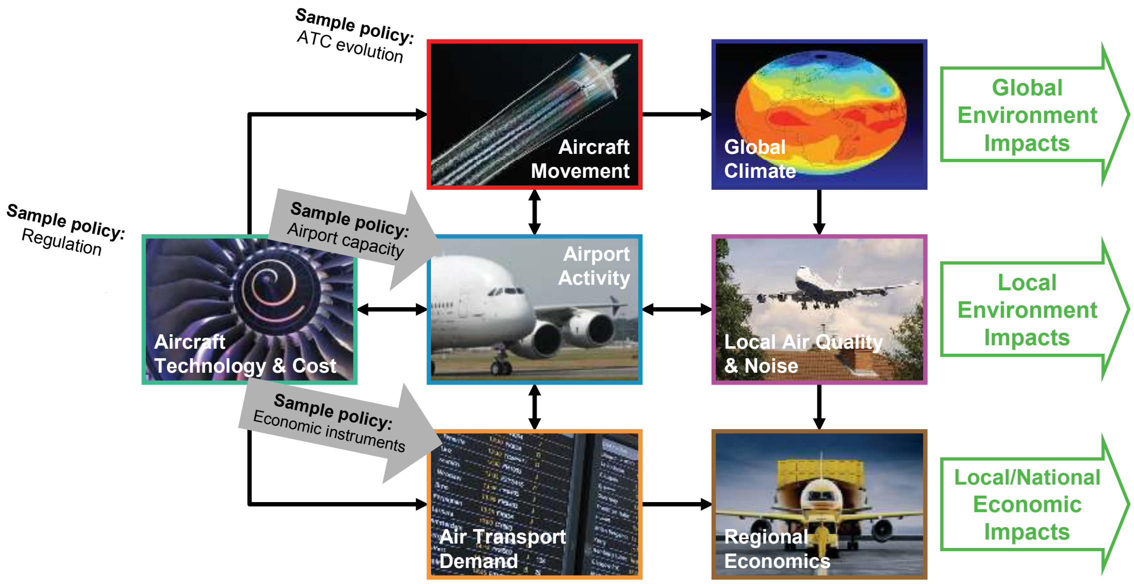

Figure 1: Aviation Integrated Modelling General Architecture

This architecture of interacting modules is designed to capture major interdependencies (allowing data transfer and feedback) and for different trade-offs to be examined, for example between competing environmental and economic metrics. The modular nature has other significant benefits, such as allowing the temporal and spatial resolution of each element to be tailored to the application being considered; a subset of modules to be run independently if the others are not required for a given application; and module definitions from other groups to be substituted into the integrated structure as desired (subject to appropriate interfaces existing). It also permits extension of capabilities and subsequent phases of development will focus on expanding capabilities in line with needs, for example to include modelling of multi-modal passenger decision options or to capture emerging trends in air transportation system evolution (e.g. future regional demand change or widespread introduction of Very Light Jets).

The architecture is also designed to fulfill the policy assessment goal of AIM: each module provides an input site for candidate policy "levers" that can be employed to manipulate the future evolution of the air transportation system and hence to assess their environmental and economic impact via the metrics produced from the impact modules, as illustrated in Figure 1. For example, regulation and certification changes can be applied to the Aircraft Technology and Cost Module; air transportation infrastructure changes in terms of airport capacity and ATC system evolutions can be applied to the Airport Activity and Aircraft Movement Modules respectively; and economic instruments can be applied to the Air Transport Demand Module. More complex policy scenarios, such as those associated with emissions trading schemes, require consideration of impacts on multiple modules simultaneously.

This general architecture belies the depth and breadth of modelling necessary to meet the project goal, as illustrated by the complexity of the interacting elements that become evident at one level deeper abstraction shown in Figure 2. The following sections describe each of the AIM modules in greater depth and should be read with reference to the detailed architecture diagram to illustrate the composition, function and relationship of the various modules. Note that this architecture only represents the functionality of AIM currently in existence or under development. Future papers will reflect the results of on-going enhancement efforts.

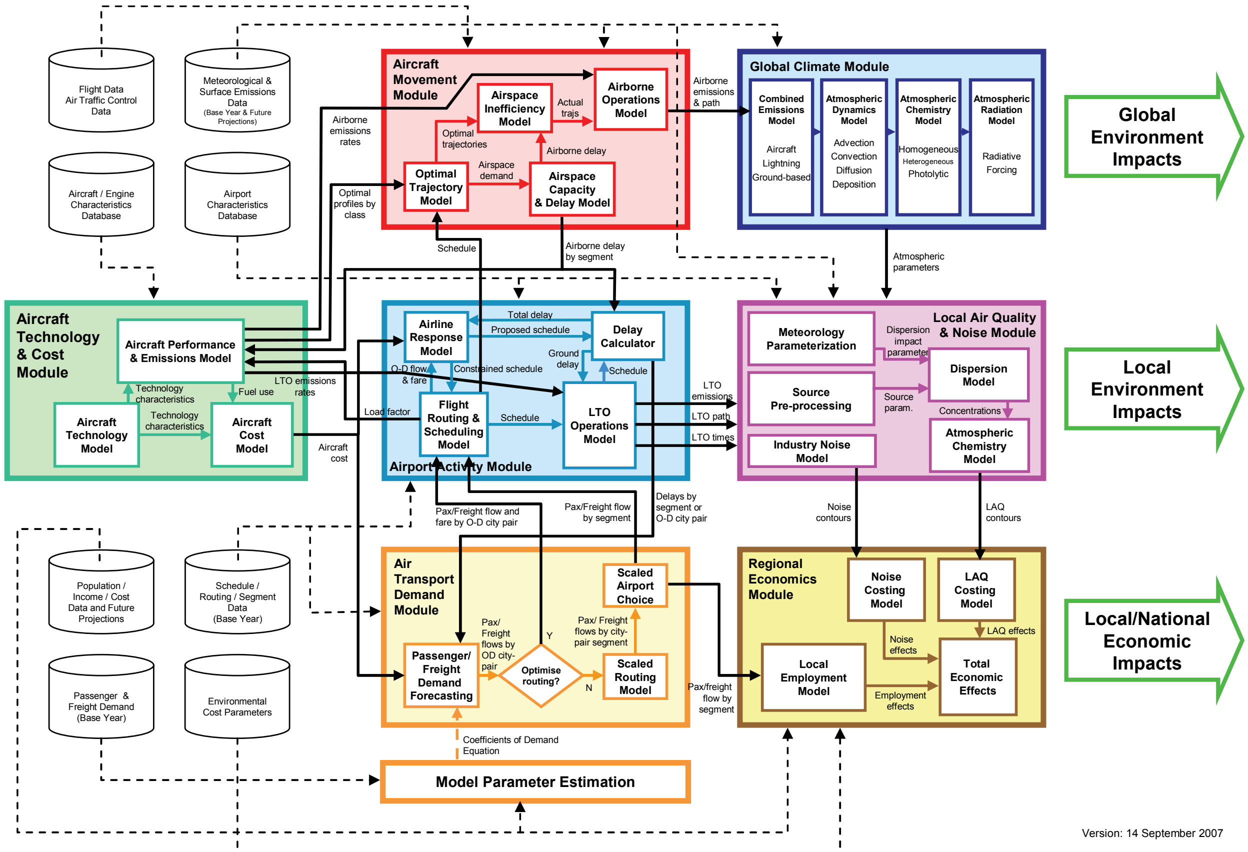

Figure 2: Aviation Integrated Modelling Detailed Architecture

A. Aircraft Technology and Cost Module

The goals of the Aircraft Technology & Cost Module include modelling aircraft performance, fuel use, emissions and operating costs for airframe and engine technology levels likely to have an effect within the forecast horizon.

The *Aircraft Performance & Emissions Model* captures the performance aspects of the aircraft at different points of the trajectory during typical "gate-to-gate" flight phases. Aircraft/engine technology levels are considered in the *Aircraft Technology Model*, including current and proposed future technologies[1] such as blended-wing bodies, open rotor engines, advanced combustors and more extensive use of biofuels. In order to obtain a sufficient representation of the spectrum of aircraft technologies operating within the global air traffic network, a limited number of "classes" of aircraft are considered covering different size, range and technology level categories.

The outputs from these two models include reference flight trajectories, fuel consumption and emissions indices as a function of flight phase and aircraft class. The Airport Activity Module utilises the emissions data during the LTO flight phases (including engine idling while stationary on the ground, taxiing from the terminal area, taking off to 3000 ft, landing from 3000 ft and taxiing back to the terminal area), while the Aircraft Movement Module utilises the data for flight operations above 3000 ft (i.e. climb, cruise, descent and airborne holding).

The technology and fuel use characteristics are used in the *Aircraft Cost Model* in order to capture the direct operating cost implications of a given aircraft technology, including variable (e.g. fuel, airport and en route charges, flight and cabin crew, maintenance) and fixed (e.g. depreciation, insurance) elements. This model will capture the feasibility of possible future technological improvements: a technology that has major environmental benefits but which is extremely expensive is unlikely to be widely deployed within the air transportation system. As a result, the *Aircraft Cost Model* will help prioritise further research and development activities.

B. Air Transport Demand Module

The Air Transport Demand Module forecasts true origin/ultimate destination (O-D) passenger and freight demand within the global air transport network. The module structure is designed to allow the use of various types of demand models or external estimates, based on the data available and the appropriate level of detail required for the policy scenarios being examined. In the initial AIM implementation, a simple model is used which accounts only for passenger demand. This relies on key explanatory variables which are available or inferable for most of the world. O-D demand between cities *i* and *j* is modeled with a one-equation gravity-type model[2]:

$$D_{ij} = (I_i I_j)^{\alpha} (P_i P_j)^{\gamma} e^{\delta A_{ij}} e^{\varepsilon B_{ij}} C_{ij}^{-\tau} \quad (1)$$

where *I* is average local per capita income; *P* is the greater metropolitan area or equivalent population; *A* and *B* are binary variables indicating whether one or both cities in the pair have qualities which might increase visitor numbers (e.g. a major tourist destination or capital city); *C* is the generalized cost to a passenger of air travel between the cities and the exponents give the elasticity of demand to each of the explanatory variables (i.e. % change in demand for % change in each explanatory variable). These exponents can be estimated by calibrating the equation against available demand data for current and past years. Future demand is estimated using forecasts of the key explanatory variables. Parameters are estimated separately for short-haul, medium-haul and long-haul journeys, as well as for different world regions. For the studies detailed in this paper, all parameters are significant at the 95% confidence level and the R^2 obtained ranges from 0.46 to 0.83, where the lower value is for short-haul routes for which the lack of competing modes in this model formulation has a strong effect. Since the cost variable includes the cost of journey duration via the value of a passenger's time, it is possible to include the demand-reducing effect of increased journey time as well as that of increased fares. Estimates of future population and GDP growth can be obtained from the IPCC Special Report on Emissions Scenarios[3] (SRES). Whilst the SRES scenarios have attracted some criticism[4], they are appropriate models to use in the context of AIM because they provide integrated scenarios of population, GDP and global ground-level emissions, allowing the Air Transport Demand Module and Global Climate Module to operate with the same input assumptions.

Once O-D demand has been estimated for a set of city-pairs, it needs to be converted into a flight schedule, i.e. flight routing and frequency. The *Scaled Routing Model* provides a simple approach to routing in which demand between city-pairs is converted to demand per flight segment. The same approach as in Ref. 5 is used, assuming that the proportions of traffic taking different routes within the hub-and-spoke system for a given O-D pair remain unchanged from the routing used in the base year. The *Scaled Airport Choice Model* performs a similar calculation for multi-airport cities for which the proportions of passengers on each city-pair segment choosing each airport are extracted from base year data[6] and assumed to remain constant. In later versions of the model, routing and airport choice will be handled by an airline response model in the Airport Activity Module discussed in the next section.

It is anticipated that future versions of the Air Transport Demand Module will consider passenger mode choice, freight transport and the differing elasticities of demand for business and leisure travelers.

C. Airport Activity Module

The purpose of the Airport Activity Module is twofold: to forecast air traffic growth as a function of passenger and freight growth; and, as a function of this growth in air traffic, model ground and low altitude operations and congestion to determine LTO emissions.

The *Flight Routing and Scheduling Model* forecasts air traffic growth according to segmented passenger and freight flows input from the Air Transport Demand Module, and outputs aircraft trips in the form of a flight schedule to the Aircraft Movement Module and internal *LTO Operations Model*. The generation of the schedule includes identification of aircraft types operated and flight frequencies by flight segment. In the current implementation of the model, the proportion of different aircraft types used on each segment is estimated as a function of forecast passenger demand, segment length, and traffic type (hub-hub, hub-spoke, or point-to-point) according to a multi-variate regression on historical data, while flight frequencies are forecast by applying base year passenger load factors (which are assumed to remain constant) to the forecast passenger demand. Both approaches are similar to those used in Refs. 7 and 8. The resulting schedule is not limited by any system capacity constraints.

As an alternative to the *Scaled Routing Model* in the Air Transport Demand Module, the *Flight Routing and Scheduling Model* is designed to capture airline strategic responses to avoid excessive delays at capacity-limited airports by interfacing with an internal *Airline Response Model*. The *Airline Response Model* is under development and has not been implemented in the version of the model used in the case study later, but it will provide a unique capability among aviation policy assessment tools to capture airline strategic routing and scheduling responses to limited airport capacities and resulting delays. A constrained flight schedule is then output to the Aircraft Movement Module and *LTO Operations Model*. This approach will allow a number of airline responses to delays to be captured, including flattening schedules, increasing aircraft sizes, and changing network routing to avoid congested hubs and make increased use of secondary airports.

The *Delay Calculator* estimates flight delays, both on the ground and in the air, due to airport capacity constraints. Airport capacities are input from available data or, if unavailable, are estimated as a function of known airport characteristics. Delays due to airport capacity constraints are added to gate departure delays due to mechanical failures and late arrivals, which are assumed to remain approximately constant (assuming schedule padding increases to maintain schedule reliability), and delay due to en route ATC and weather (input from the Aircraft Movement Module). This represents average flight arrival delay, i.e. the increase of travel time over the unimpeded, and is output to the Air Transport Demand Module and, in future implementations of the module, to the *Airline Response Model*. Delays due to airport capacity constraints are estimated using queuing theory, applying the cumulative diagram approach and steady state simplifications[9]. In future developments this model may be upgraded to a full network queuing simulation to improve accuracy. Delays due to destination airport capacity constraints are distributed between the air and ground according to an airborne holding threshold calculated for each airport from historical delay data, and above which delay is assumed to be propagated upstream to the departure gate. If delays are sufficiently high to cause departure and arrival queues to remain into the following operational day, all aircraft remaining in the queue are assumed to be cancelled. Delays in each phase are output to the *LTO Operations Model*, which estimates aircraft emissions.

The *LTO Operations Model* models aircraft ground operations and flight operations below 3000 ft (thus including taxi, take-off, initial climb, final approach and landing). The outputs of this model are LTO path, taxi and flight times, and emissions (calculated from emissions by aircraft type input from Aircraft Technology & Cost Module), which are direct inputs to the Local Air Quality & Noise Module. Ground operations are modeled as a function of average unimpeded taxi times and taxi delays estimated by the *Delay Calculator*. Average unimpeded taxi times are obtained directly from data, where available, whilst parametric modelling based on other airport characteristics is required for airports for which it is not available. Taxi delay is split between active taxiways, where engines are assumed to run at idle, and parking areas, where engines are assumed to be switched off. Aircraft are assumed to park if taxi delay is greater than a threshold of 1 hour. This number is an estimate, but will be refined in future work. Flight operations below 3000 ft are modeled according to take-off, initial climb, final approach and landing times by aircraft class, which are predicted by the Aircraft Technology & Cost Module.

D. Aircraft Movement Module

The main objective of the Aircraft Movement Module is to identify the location of emissions release from aircraft in flight, accounting for inefficiencies and airborne delays introduced by the ATC system.

The *Optimal Trajectory Model* converts the schedule and aircraft class in each segment to a generic airborne trajectory. This comprises a four-dimensional route consisting of a great circle route (i.e. the shortest distance) between the relevant city pairs flown at the optimal vertical and speed profile for each aircraft class. In reality, the route and time flown in executing a given flight segment will be degraded from this optimum by various constraints within the ATC system, and this process is handled in the *Airspace Inefficiency Model*. This degrades the actual trajectories from the optimum profiles to account for inefficiencies for the airspace being flown through due to air traffic control and management techniques. These inefficiencies can be present for a number of reasons, including airspace structures (e.g. standard routes, and flight levels), airspace restrictions (e.g. "no-fly"/military zones, convective weather), conflict avoidance (e.g. keeping aircraft separated by at least the required separation minima), and airspace delay. Different parts of the world and different evolutions of the system into the future have different inefficiency metrics associated with them. Current characteristics for some parts of the world are being determined from radar track analysis (e.g. from the US Enhanced Traffic Management System) or published data[10]. Other regions and future manifestations of the world systems are being estimated, for example from examination of ATC charts and assessment of possible future traffic redistribution and modifications to routing structures for different regions of the world (e.g. after Single European Sky (SESAR) and US NextGen implementations).

Incorporating airspace delay is handled by the *Airspace Capacity and Delay Model*. Airspace delay is relevant to both the inefficiency calculation and is one of the elements required by the Airport Activity Module to determine total system delay. Airspace capacity is a complex function of many factors, such as sector size; shape; number of entry and exit points; traffic complexity; structural complexity; separation minima and surveillance level, while airspace sector demand is a similarly complex function of multiple variables such as route configurations, weather and traffic distribution at any given time. In order to simplify these aspects to make the model appropriate for the AIM application, published historical en route delay data as a function of traffic level is being used and extrapolated into the future. The advantage of this approach, apart from its simplicity, is that operational data inherently contains "real-world" effects (such as those outlined above) which are prohibitively complex to model accurately. If a more complex model is required in later evolutions of AIM, a simplified model could be developed where the global airspace is discretized into rectangular airspace sectors, each with a capacity dependent on the airspace categorizations used for the inefficiency metric determination. Delay could then be determined by the difference between capacity and demand at a given time in each of these sectors using queuing theory techniques similar to those employed in the Airport Activity Module and in Ref. 11.

From this set of processes, modifications to the optimal 4D trajectories are made in the *Airborne Operations Model*. The inefficiency factors are applied in the various axes to generate the actual predicted route, distance and time involved in a given flight segment. The complete set of trajectories across all segments in the schedule received from the Airport Activity Module is converted to emissions (using information from the Aircraft Technology & Cost Module) and distance flown by grid cell and altitude layer (typically 1º latitude by 1º longitude by 1000 ft vertically) for the region of interest. This information is then output to the Global Climate Module.

E. Global Climate Module

The Global Climate Module determines the impact on the global climate system of the aircraft emissions identified by the Aircraft Movement Module. It will consider the effects of carbon dioxide, nitrogen and sulphur oxides, contrails, and stratospheric water vapor emissions.

The following processes are considered at varying degrees of detail and complexity. The aircraft emissions are combined with ground-based (using appropriate scenarios of their evolutions) and naturally-occurring levels of the various species of interest in the *Combined Emissions Model*. The *Atmospheric Dynamics Model* captures the advection, convection, diffusion and deposition processes inside the global atmosphere, while chemical changes are captured in the *Atmospheric Chemistry Model*. Finally, an *Atmospheric Radiation Model* produces climate impact metrics that provide the ability to assess the global impacts of a variety of policy options applied to the preceding AIM modules, but can also serve as input for economic costing ("monetisation") calculations.

The implementation of these processes can be performed in one of three different configurations depending on the application being studied. All are based on established and validated atmospheric model capabilities that are specifically adapted for use in the integrated context of AIM. The most complex configuration consists of an atmospheric general circulation model with coupled modules for chemistry and radiation[12]. This model calculates its own meteorological data and allows for the additional consideration of feedback mechanisms between atmospheric transport, chemistry, and radiation. A further advantage of this configuration is the ability of the general circulation model to simulate future meteorological conditions, thereby allowing a more realistic prediction of the environmental impact of air traffic in future decades. However, this configuration is very computationally intensive, so a reduced complexity configuration consists of a global three-dimensional atmospheric chemistry transport model[13]. This uses external meteorological data to calculate the transport of chemical species, such as greenhouse gases and their precursors, and their chemical interactions. The calculated changes in the atmospheric composition are fed into an off-line radiative module which calculates the radiative forcing impact. The advantage of this configuration is the use of meteorological data which, together with aircraft movements, permits the realistic reproduction of the atmospheric impact due to near-term global air traffic. The lowest complexity configuration consists of a simplified parametric version of the chemistry transport model used in the second configuration and the off-line radiative module. This is based upon recent scientific findings[14] which indicate that, under certain conditions, the impact of small perturbations applied to the present-day aircraft emissions can result in a linear response in the impact on greenhouse gas concentrations. The advantage of this configuration is the ability to quickly perform a large number of sensitivity studies (strictly within the valid parametric range) at comparatively low computational cost, making it highly suitable for the AIM application.

F. Local Air Quality and Noise Module

The Local Air Quality & Noise Module investigates dispersion of relevant pollutants and assesses noise impacts in the vicinity of airports. Local air quality (LAQ) and noise impact assessments are undertaken in AIM simulations for a large set of airports, and as such models with an appropriately low computational cost are required, similar to the requirements just discussed for the Global Climate Module.

There are a number of widely-used operational atmospheric dispersion models applied to airports, including ADMS-Airport, EDMS and LASPORT. All have been widely applied and evaluated against experimental results, but require run times of several days when applied to a year of data for a large airport, such as Heathrow or Chicago O'Hare. For AIM, a simple statistical model has been developed suitable for determining the long-term statistics of pollution concentrations. Previous studies (such as Ref. 15) imply that NO_2 and Particulate Matter (PM) are of significance in an airport context. For simplicity, the AIM air quality model has been designed only to treat inert pollutants. NO_x chemistry is applied using empirical correlations (e.g. Ref. 16) and deposition over the scales of interest is neglected. While ground-level ozone impacts may be significant, these are controlled by larger regional scale processes beyond the scope of the current approach.

The AIM air quality model is based on a 'dispersion impact parameter', which parameterizes annual average pollutant concentrations as a function of direction from an emission source. An approximation relating to the importance of lateral dispersion over long-term averages is also used, which affords significant computational savings when concerned with calculating long-term average pollutant concentrations. These approaches combined yield a runtime saving of several orders of magnitude as compared to direct modelling methods.

Dispersion impact parameters can be calculated from (in order of increasing accuracy and complexity): wind roses under simplifying assumptions regarding atmospheric stability; simplified theories of atmospheric dispersion and the influence of stability; and parameterizations using advanced regulatory models such as ADMS and AERMOD. This allows air quality impact assessments in AIM to scale with the availability of local meteorological data and the significance of the airport in question. Further details on the development of this method can be found in Refs. 17 and 18. The module will enable the assessment of aviation policy LAQ implications, particularly in the context of the European and US regulatory frameworks. Policies under study include part-time/dynamic mitigation strategies, for example encouraging particular operational procedures under certain wind conditions known to cause local air quality problems. In addition, LAQ contours are fed to the Regional Economic Impacts Module to assess their wider effects, for example by costing their impacts on health in local communities around airports.

The purpose of the noise component is to assess the noise impacts of the operations being modelled in the Airport Activity and Aircraft Movement Modules. Several industry-standard codes are available (e.g. the FAA's Integrated Noise Model (INM) and Wyle Laboratories NMSim) and these are utilized in the module to assess the noise impacts of key variables, including different fleet mixes and routing structures. The codes can assess impacts against a variety of metrics, including various noise metrics (e.g. LAmax and DNL contour locations and areas) and population exposure. These are fed to the Regional Economics Module to assess impacts such as property valuation impacts or other societal costs of location within a given noise contour.

G. Regional Economics Module

This module quantifies the impact of aviation on regional economies, including the increase in direct and indirect employment opportunities in the region. Direct employment results from the jobs related to aviation and airport operations, whereas indirect employment results from backward (e.g. caterers for in-flight catering) or forward linkages (e.g. improved investment climate because of lower transport costs)[19]. There are also negative environmental impacts due to the presence of an airport, such as increased noise, poorer local air quality and climate impacts. These may have an effect on the regional economy as well: local pollutants may increase morbidity and health care costs, while noise may depress property prices. Rather than running a full economic simulation of each local area (which can be data intensive and computationally costly), current efforts involve an extensive literature survey. This will provide a rigorous but concise description of the local impact of airports in different regions of the world in terms of quantitative estimates of the current and future economic impact of the aviation sector, both regionally and in terms of national GDP. The ambient air quality or noise impact information from the Local Air Quality and Noise Module mentioned above will be converted to economic effects through appropriate 'conversion factors' determined from the literature survey. This module is in a very early stage of development, so will not be considered further here, but results from the regional economics analysis discussed above, as well as possible expansion to global economic and social effects, will be discussed in future publications.

III. Case Study: United States Air Transportation System Scenarios

A. Case Study Introduction

The United States air transportation system is the largest of any region in the world. Although larger growth is expected in the future in the Asia Pacific region[20] (driven by rapid economic expansion), the US was selected for this case study because of the availability of data and the large number of other analyses of the region (e.g. Ref. 5, 21, and 22) enabling comparison between model outputs to be made. Other regions, particularly South and East Asia, will be examined in detail in future work. This case study includes a forecast of air transport passenger demand between 50 major airports[***] in the United States, from 2000 to 2030. Whilst the 50 airports are only a small subset of the world's airports, flights between them represent over 40% of US scheduled domestic departures

[***]The IATA code of the 50 airport set is ABQ, ATL, BDL, BNA, BOS, BUR, BWI, CLE, CLT, CVG, DAL, DAY, DCA, DEN, DFW, DTW, EWR, FLL, HOU, IAD, IAH, IND, JFK, LAS, LAX, LGA, MCI, MCO, MDW, MEM, MIA, MSP, MSY, OAK, ONT, ORD, PBI, PDX, PIT, RDU, SAN, SAT, SDF, SEA, SFO, SJC, SLC and STL.

in 2000 and nearly 20% of the world's scheduled flights. The study's base year was selected for compatibility with previous work on the US domestic system (it is easily updated subject to data availability) and, although the capability exists to extend the models to 2100, this forecast is not extended beyond 2030 because of the high uncertainties associated with longer time horizons.

Three scenarios were run to illustrate the importance of feedback of data between modules to capture system-wide interactions and to illustrate the utility of the modelling approach for analysis of a simple policy scenario:

- **Scenario 1: Unconstrained/No Feedback.** With no feedback of the effects of limited system capacity causing delay, air transport passenger demand and resulting operations are assumed to grow unconstrained.
- **Scenario 2: Feedback of Delay Effects.** By introducing feedback, the effects of limited system capacity can be modeled. In this scenario, a simplified airline response to delay is assumed where 50% of the costs incurred by the airline due to delays are passed directly to passengers in the form of higher fares. Identification of a solution for this scenario requires iterative convergence between the Air Transport Demand Module and Airport Activity Module to feed back airline costs to increase ticket prices, according to which passenger demand reduces. A new (partial) equilibrium is reached after typically 6-20 iterations. Other effects that would be observed in the real world (e.g. passenger response to increases in travel time, airline fleet/schedule adjustments and regulation) are not modeled. However, they would be expected to mitigate demand growth and hence will be studied in the future.
- **Scenario 3: Feedback of Delay Effects plus Per-Km Tax Policy.** This is the same as Scenario 2, but with a per-kilometer tax applied to tickets from the year 2020 with the objective to reduce RPKM demand in 2020 down to year 2000 levels, so that resulting delays and emissions can be directly compared.

Note that these scenarios, their associated forecasts and environmental impact results are for illustrative purposes of AIM's capabilities and do not necessarily represent realistic evolutions of the US air transportation system.

B. Data Requirements & Assumptions

Population, per capita income and airfares for the 50-airport set were obtained from US Census[23] and BTS[24] data. Demand to cities outside the set from cities inside was assumed to grow by the same factor to within-set demand. The case study uses the SRES B2 scenario, which is based on the United Nation's medium population growth model[25]. Other SRES scenarios typically produce slightly higher demand projections: for example, unconstrained demand growth under the A2 scenario results in a 4 times increase in US domestic RPKM between the year 2000 and 2030, whereas in the unconstrained B2 scenario this increase is only 3.5 times. It is assumed that US domestic air travelers have a value of time of approximately $30/hr, where all monetary values quoted are in year 2000 US dollars[26] and that, in the absence of any extra taxes, charges or airline cost feedback, average fare continues to follow its historical slow decreasing trend of 1.55% per year.

In the modelling of flight delay, airport capacities were assumed to be the annual average of capacities reported by the FAA at each airport in 2000, extracted from the ASPM database[27]. Increases in these airport capacities were made according to those predicted in the Airport Capacity Benchmark Report 2004[28] due to planned new runways and technological/procedural improvements included in the FAA Operational Evolution Partnership (OEP) v5.0, which extends from 2003 to 2013. Because no specific dates within this time period are given for each airport capacity increase, all were assumed to become operational in 2013, with no further increases thereafter.

The aircraft performance elements were modeled following the EUROCONTROL Base of Aircraft Data (BADA)[29]. This is a simplified model based on one energy equation relating the rate of work done by the forces acting on the aircraft to the rate of increase in potential and kinetic energy. The database provides performance and operating procedure coefficients to solve the equation for different flight phases for a large number of current aircraft types. Data corresponding to the B737-300 was used to represent aircraft with up to 189 passenger seats, while the B767-300ER and the B747-400 were used for aircraft with between 190 and 300 and above 300 seats respectively. Airline costs were estimated according to reported operating costs[24] averaged for these types over all reporting airlines.

Optimal trajectories between the 50 US airports were modeled via great circle lateral routes and did not account for any wind effects. Airspace lateral inefficiency effects were calculated from an analysis of 24 hours of ETMS radar data of US traffic to derive a relationship between lateral inefficiency and route length. This was used to extend the distance flown between each city-pair by an appropriate amount. For simplicity, vertical and speed inefficiencies and en route delays were neglected. Future studies will examine these issues in detail and appropriate effects will be included in later analyses.

Radiative forcing impacts of the en route CO_2 emissions in the different scenarios were calculated using a simplified expression given in the IPCC TAR[30]. The increase in CO_2 emissions, originally over the U.S., was assumed to be evenly distributed over time on a global scale. Atmospheric CO_2 mixing ratios for 2000 were set to standard literature values. Increases in other CO_2 sources between 2000 and 2030 were not taken into account. This calculation does not determine the full climate impact of a regional air traffic increase but rather shows the increase in global radiative forcing due to a regional growth in emissions of CO_2 in a present-day atmosphere.

Local air quality impacts were calculated for Chicago O'Hare International Airport (IATA code ORD) by the AIM air quality model under several simplifying assumptions. In particular, emissions were allocated to six area sources representing runways and one area source representing terminal area/taxi emissions. A sample of representative meteorological data from the US National Weather Service meteorological station at ORD was used. Only aircraft sources were considered and the statistical correlation between emission rates and meteorological conditions was neglected. Runway usage was based on an analysis of historical trends.

C. Results

The main focus in the scenarios is on the interactions between the Air Transport Demand and the Airport Activity Modules, and this is highlighted in the results of Figure 3. However, the en route and local airport emissions results presented afterwards utilize the capabilities of the other modules in AIM's integrated structure.

Forecasts from 2000 to 2030 for annual demand in terms of Revenue Passenger-Km (RPKM) from the Air Transport Demand Module; and total system aircraft operations, system average arrival delay and local NO_x emissions at ORD from the Airport Activity Module for the three scenarios are presented in Figure 3. The demand forecasts include those from Airbus[31], Boeing[32], ICAO[33] and AERO-MS[34] for comparison: those with (NA) appended apply to the North American rather than just the US market. Because they apply to different route groups and time periods, the start year total RPKM value in each case has been normalized to the historical value for the 50 airports extracted from US DOT T100 data.

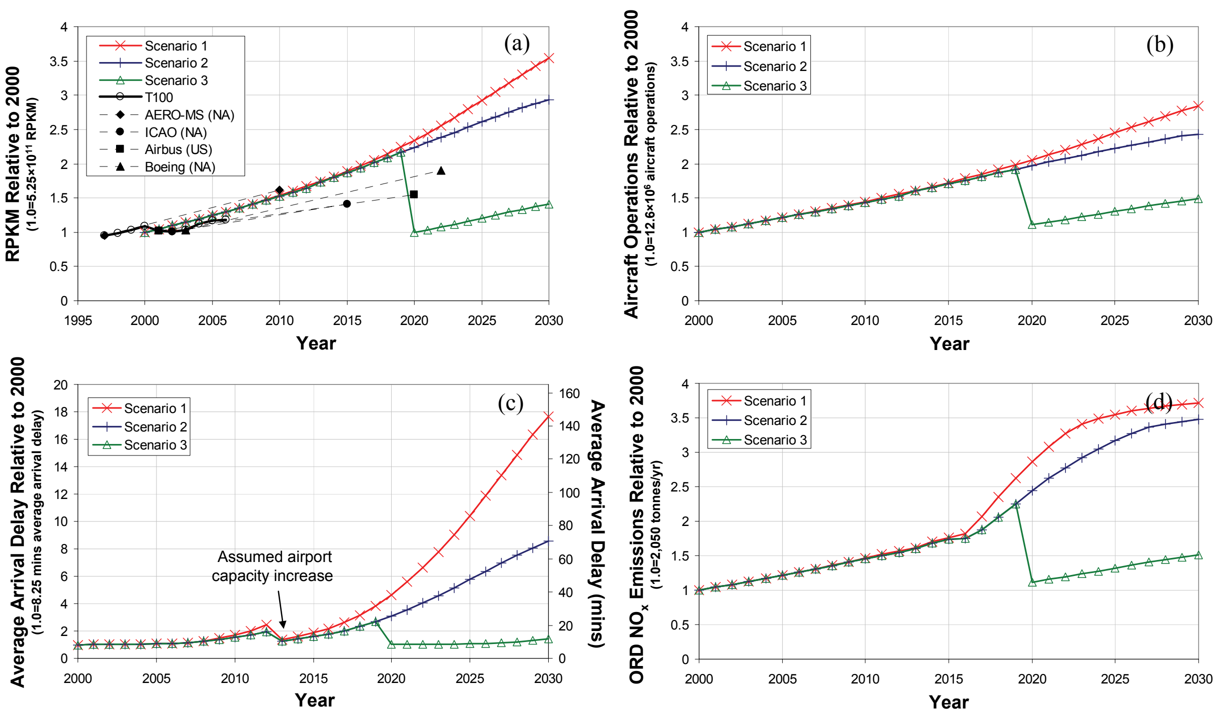

Figure 3: Forecasts of (a) System Revenue Passenger-Km growth; (b) Total System Aircraft Operations; (c) System Average Arrival Delays; (d) LTO NO_x Emissions at ORD

The results for Scenario 1 show demand growth corresponding to an RPKM increase of 3.5 times the 2000 level by 2030. This is on the high end of published estimates, as expected given the unconstrained nature of the scenario in which passenger numbers are assumed to continue to grow and airline behavior does not change even when the growth in air traffic operations causes an even stronger increase in delays. This unsustainable state demonstrates the need for feedback between delay, ticket price and demand. In the results for Scenario 2, even the relatively modest feedback of 50% of the increased operating cost to the passenger has a significant effect, particularly over longer timeframes. Forecasts of demand show a 20% reduction, annual system operations show a 15% reduction and average arrival delay shows a 50% reduction in Scenario 2 relative to Scenario 1 by 2030. The number of aircraft operations presented in Figure 3b are forecast to grow less rapidly than demand (2.8 times the 2000 levels by 2030 under Scenario 1) because increased demand is accommodated with larger aircraft types. Then the reduction in operations from Scenario 1 to 2 is less than the observed reduction in demand because the proportion of smaller aircraft is greater in Scenario 2. Scenario 3 results illustrate the effects of the distance-based tax: in order to reduce the RPKM demand to 2000 levels in 2020, a 7.7 cents/km charge is required, equating to an additional $300 on a ticket from New York to Los Angeles.

Closer inspection of the results reveals additional interesting insights enabled by AIM's integrated structure. The arrival delay results (Figure 3c) show a gradual increase in delays to 2012 for all scenarios, at which point delays reduce sharply corresponding to the increases in airport capacity predicted in Ref. 28, and applied en-masse in 2013. Despite the non-trivial capacity increases forecast (system capacity increases by 15.3% in 2013 for the 50 airport set), delays are back to 2012 levels by 2017 in Scenario 1 and 2019 in Scenario 2. The difference in delay between Scenarios 1 and 2 in 2030 is almost double, significantly greater than the difference in number of operations. This suggests that a relatively small reduction in number of operations has a significant, and highly non-linear, effect on delays. Such behavior is expected of a system that is close to saturation. It also illustrates the effect of airline responses on delays, whereby a small reduction in operations can result in a significant reduction in delay. The delays by 2030 are, however, still unrealistically high and further airline and passenger responses must be modeled in order to accurately forecast the state of the system. This will be added in further AIM development as discussed previously. Scenario 3 shows a significant reduction in delays in 2020, which corresponds to the introduction of the charge per kilometer. In this scenario delays do not grow significantly beyond this point. This is expected as the passenger demand and number of operations is reduced to levels close to those in 2000, so the delay trend is expected to correspond to that in the first 10 years of the forecast. The Scenario 3 results also show that, although demand drops to 2000 levels after the policy has been implemented, operations are slightly higher than in 2000. This is because a larger proportion of the 2020 RPKM figure is made up of short-haul flights, since short-haul passengers contain a high proportion of business travelers[35] who are typically less sensitive to price increases. Hence the total number of operations is greater than in 2000, and so correspondingly are the delays and local emissions.

Annual local NO_x emissions at Chicago O'Hare are presented in Figure 3d. These results are representative of the more capacity-constrained airports in the 50 airport set. All scenarios show an initial gradual increase in emissions. No capacity increase is predicted at Chicago O'Hare in Ref. 28, so no change in the growth trend in emissions is expected after 2012. Scenario 1 shows a sharp increase in the growth of emissions after 2015, suggesting that this is when the airport approaches saturation. This strong growth in emissions is caused by sharply increasing delays. The growth in emissions decreases, however, beyond 2022. This is because of the thresholds applied to restrict airborne holding and taxi delay incurred on active taxiways (and thus with the engine running). As delays climb beyond these thresholds they are incurred at the departure gate or in parking areas, both with engines switched off. Scenario 2 also shows a sharp increase in emissions after 2015, but the growth is consistently less than that in Scenario 1 because of the reduction in delays. By 2030 the difference in emissions is smaller than the difference in delays because the reduction of delays primarily occurs at the departure gate and during taxiing, where emissions are low. The significantly higher emissions during the airborne flight phases are only reduced by the reduced number of operations (routing and technology changes would also reduce emissions in the real world but these are not being modeled in the current case study). The majority of observed reduction in emissions is therefore achieved through a reduction in operations. The sharp decrease in emissions in 2020 in Scenario 3 is due to the reduced operations caused by the introduction of the charge per kilometer policy.

The annual en route CO_2 emissions in 1^o grid cells at cruise altitude (35,000 ft) and global radiative forcing perturbations for the three scenarios are presented in Figure 4. The Scenario 1 results for 2030 show a large increase in the amount of CO_2 being released at cruise altitudes relative to the 2000 baseline, with especially large amounts being released in the heavily-traveled trans-continental routes between the North-East and South-West seaboards, and the North-East to Florida. Scenario 2 results show the expected reduction of en route emissions as a result of the dampened demand and traffic growth associated with the delay cost feedback. The Scenario 3 results show that emissions increases from the 2000 baseline are evident in the system by 2030 as the traffic picks up after the 2020 step-change associated with the tax introductions, but the levels are considerably reduced relative to what they would have been without the policy. Global radiative forcing calculations for each scenario show the largest change of +8.4 mW/m^2 in 2030 is associated with the largest CO_2 emissions in Scenario 1, while smaller changes of +6.1 mW/m^2 and +1.4 mW/m^2 are observed for Scenarios 2 and 3 respectively. These changes are compared to the year 2000 baseline result of 25.4 mW/m^2, which in turn compare favorably to other published results of the absolute global radiative forcing impacts from aviation activities in 2000 (e.g. 25.3 mW/m^2 in Ref. 36).

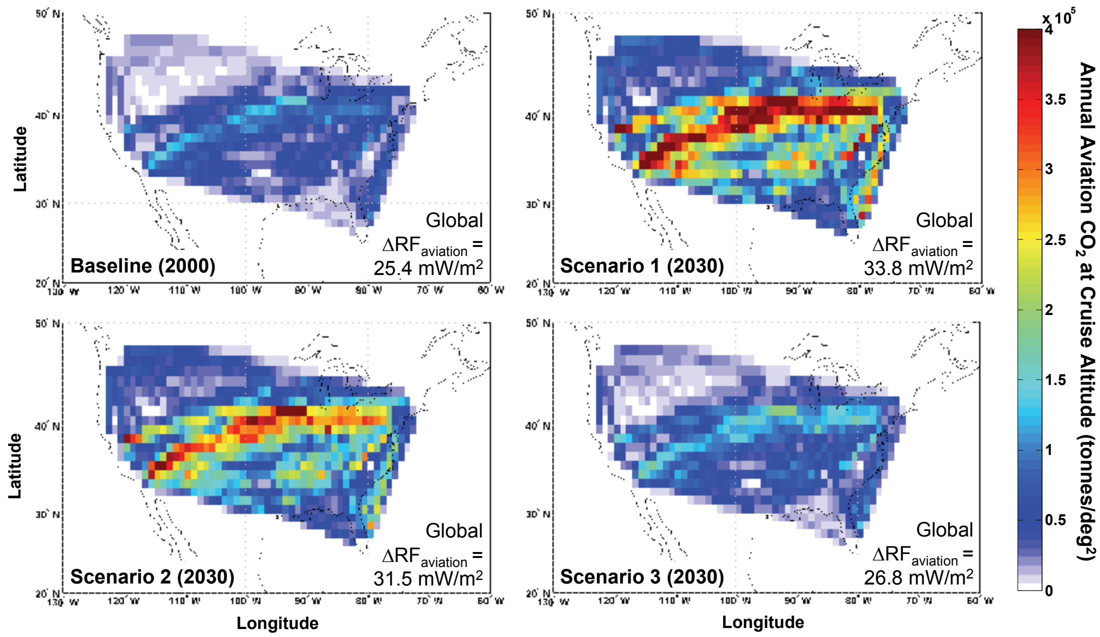

Figure 4: En Route CO_2 Emissions and Global Radiative Forcing Results

The Local Air Quality and Noise Module was used to compute NO_x concentration contours at ORD for the various test scenarios using emission rates predicted by the Airport Activity Module, and these are given in Figure 5. Note this example is for model demonstration purposes only. The airport runway structure is clearly evident in the baseline results for 2000. Ground-level NO_x concentrations increase greatly by 2030 with Scenario 1, are slightly reduced with the feedback in Scenario 2, and show smaller increases from the baseline in Scenario 3. The trend of the increasing importance of taxi and terminal emissions (represented by a rectangular area source in the center of the plots) with increasing delays is also evident. The greater NO_x concentrations to the north and east are consistent with prevailing winds at O'Hare and runway concentrations are indicative of predicted usage. While compliance with ambient air quality regulations cannot be determined from these plots (regulations are specified in terms of NO_2 and depend on emissions from all sources) the results for 2030 indicate there is a probability of violating the current US annual average NO_2 regulatory limit of 100 μg/m^3 in Scenarios 1 and 2. Furthermore, it is worth noting that a current EPA assessment of NO_x health criteria may lead to changes in the regulations in the future.[37]

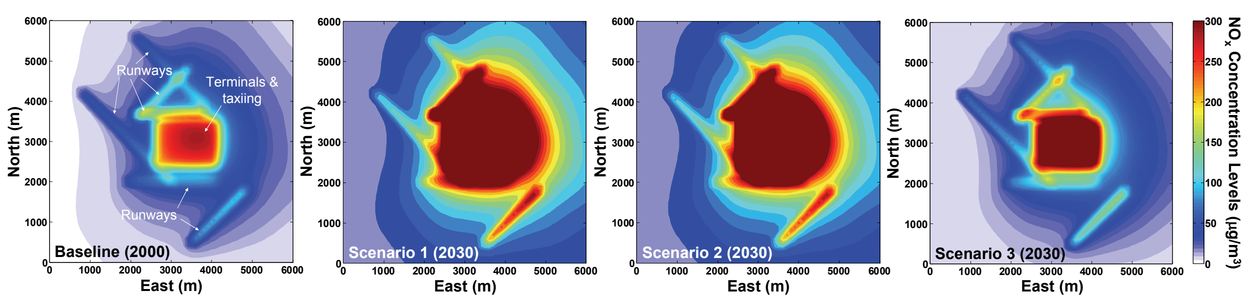

Figure 5: Annual Average NO_x Concentration Results at Chicago O'Hare

IV. Conclusions

There is an urgent need for policy assessment tools to better understand the complex interactions between the positive and negative impacts of future worldwide aviation system growth. This paper has introduced the Aviation Integrated Modelling project goals and architecture designed to provide understanding of how the air transportation system interacts with environmental and economic influences. The current functionality of the interlinking modules has been described to demonstrate the depth, breadth and integration of the elements being considered. A sample case study involving different evolution scenarios of the US air transportation system has been analyzed with the current generation model, and the results illustrate the significant insights that can be gained from the integrated nature of the AIM structure. A simple policy scenario has also been presented to show the utility of AIM to this important application. Further refinements and greater functionality will continue to be added in line with project and stakeholder needs. Current major development efforts include the addition of an airline response model to capture realistic operator response to increased delays and/or costs; modelling of worldwide passenger and freight demand with particular emphasis on the developing South and East Asia region and different types of passengers (e.g. business vs. leisure); and modelling of new aircraft and engine technologies that could be introduced within the next several decades. Results from the integration of future capabilities will be reported in subsequent papers.

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