



Modelling Environmental & Economic Impacts of Aviation

Introducing the Aviation Integrated Modelling Project



IIT Bombay Presentation

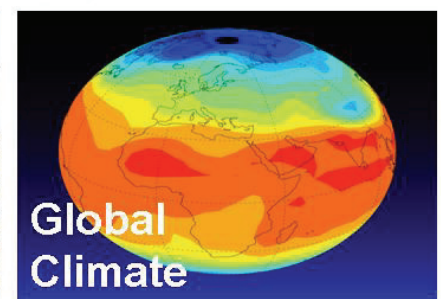
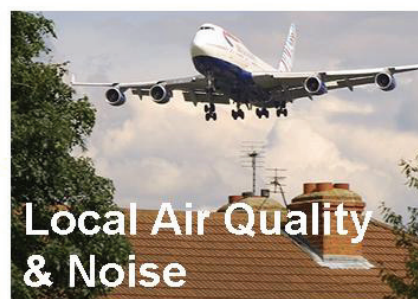
26 October 2007

- Introduction
- Project Architecture
- Modules
 - Demand
 - Aircraft Technology and Cost
 - Airport Activity
 - Aircraft Movement
 - Global Climate
 - Local Air Quality and Noise
 - Regional Economics
- Case Study
- Conclusions

- Global air transportation system continues to grow
- System is large, complex and multi-disciplinary involving numerous stakeholders with different agendas
- Range of future trends
 - ❑ Developing regions
 - ❑ Developing sectors
 - ❑ Developing technologies
- If demand continues to grow, capacity and environmental pressures will increase
- Need for tools to assist policymakers...



- **Goal:** Develop policy assessment tool for aviation, environment & economic interactions at local & global levels, now and into the future
 - Assess policies to strike appropriate balances between economic benefits and environmental impact mitigation
 - Independent & transparent tool for mediating between stakeholders
 - 3 year project started October 2006



Core team:

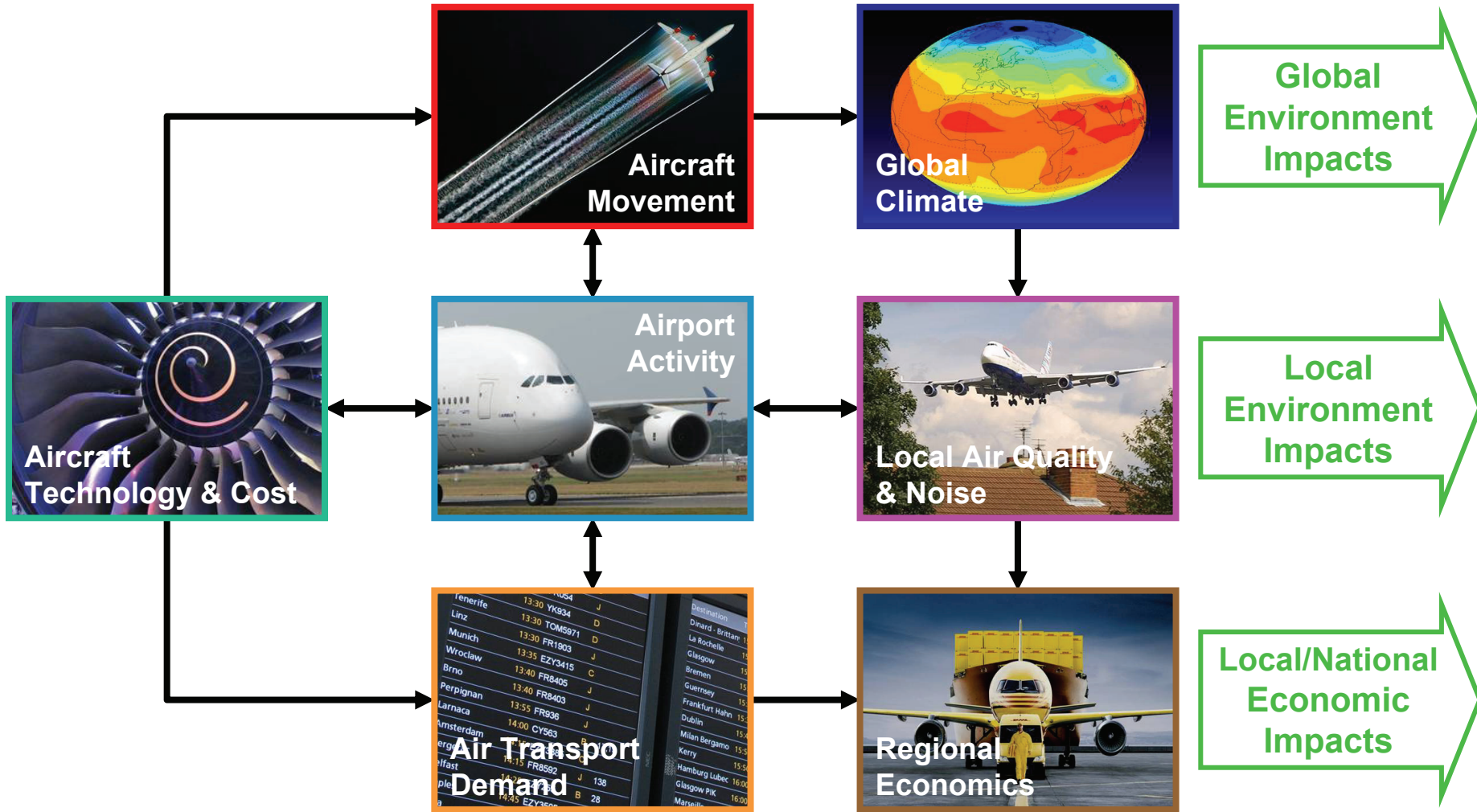
- Dr. Andreas Schäfer (*Principal Investigator*)
- Steven Barrett (*Local Air Quality & Noise*)
- Dr. Lynnette Dray (*Air Transport Demand*)
- Antony Evans (*Airport Activity*)
- Dr. Marcus Köhler (*Global Climate*)
- Dr. Tom Reynolds (*Project Manager & Aircraft Movement*)
- Dr. Maria Vera Morales (*Aircraft Technology and Cost*)
- Zia Wadud (*Regional Economics*)

IAE co-investigators:

- Prof. Rex Britter (*Engineering*)
- Prof. Bill Dawes (*Engineering*)
- Dr. Chez Hall (*Engineering*)
- Prof. Peter Haynes (*Applied Mathematics & Theoretical Physics*)
- Prof. Roderic Jones (*Chemistry*)
- Dr. Jonathan Köhler (*Economy*)
- Prof. John Pyle (*Chemistry*)
- Dr. Helen Rogers (*Applied Mathematics & Theoretical Physics*)

Affiliated students:

- Henry Hallam (*Engineering*)
- Richard Hunsley (*Engineering*)



- **Integration**

- Captures interdependencies, data transfer & feedback
- Examination of trade-offs (e.g. local environment vs. global environment vs. economic impacts)

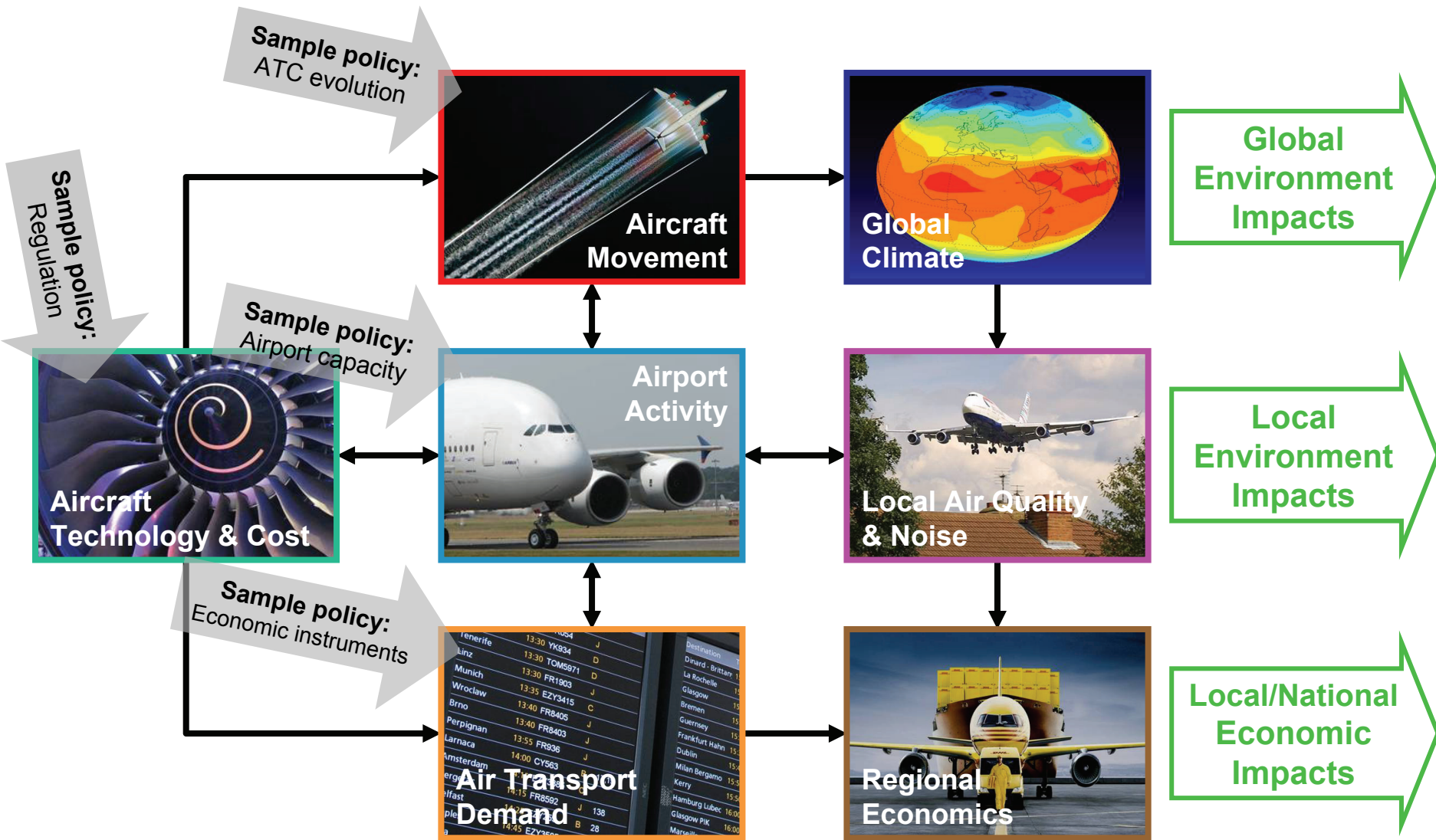
- **Modularity**

- Resolution of modules tailored to application
- Subset of modules run independently
- Substitution of models from other groups

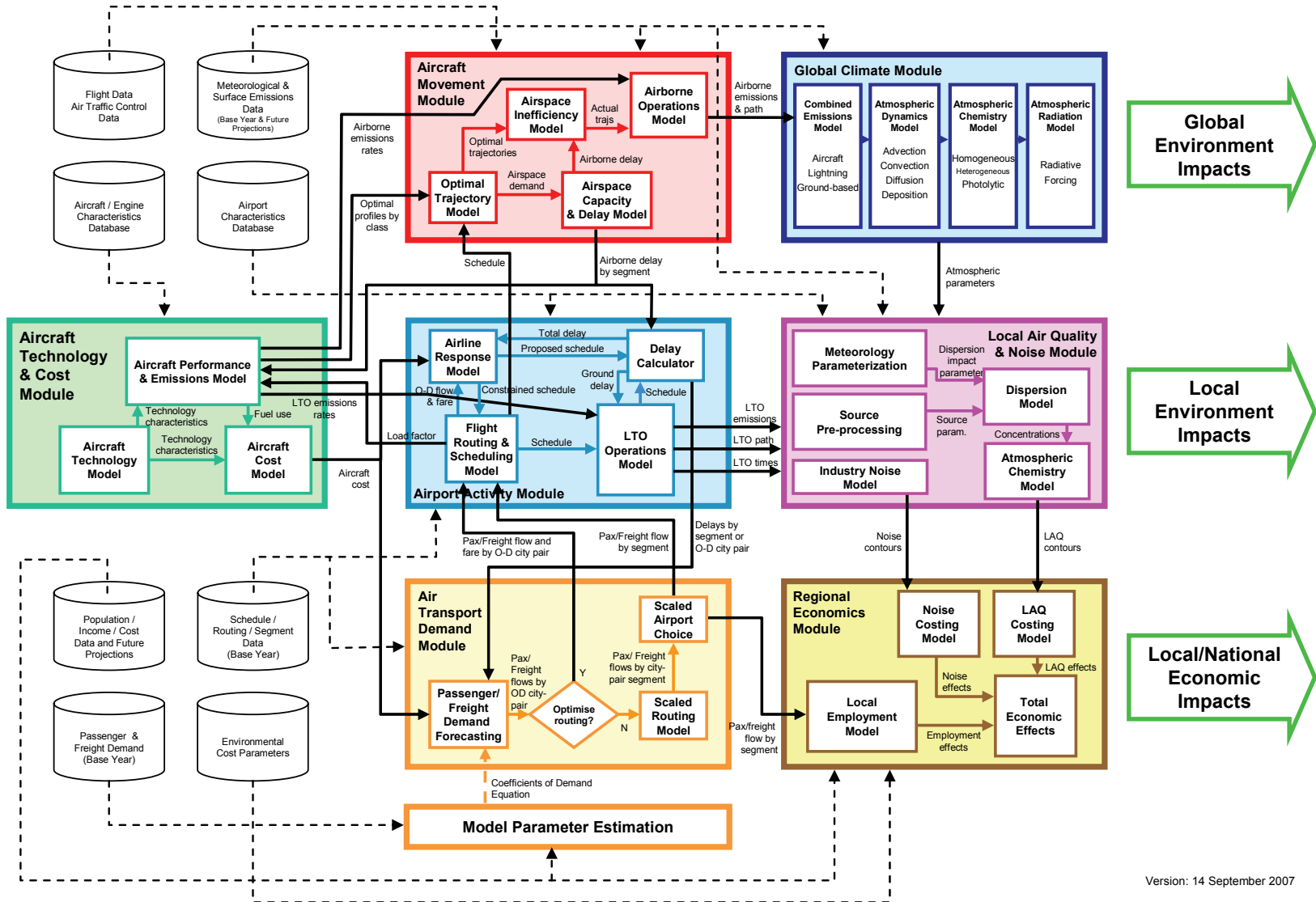
- **Extendability**

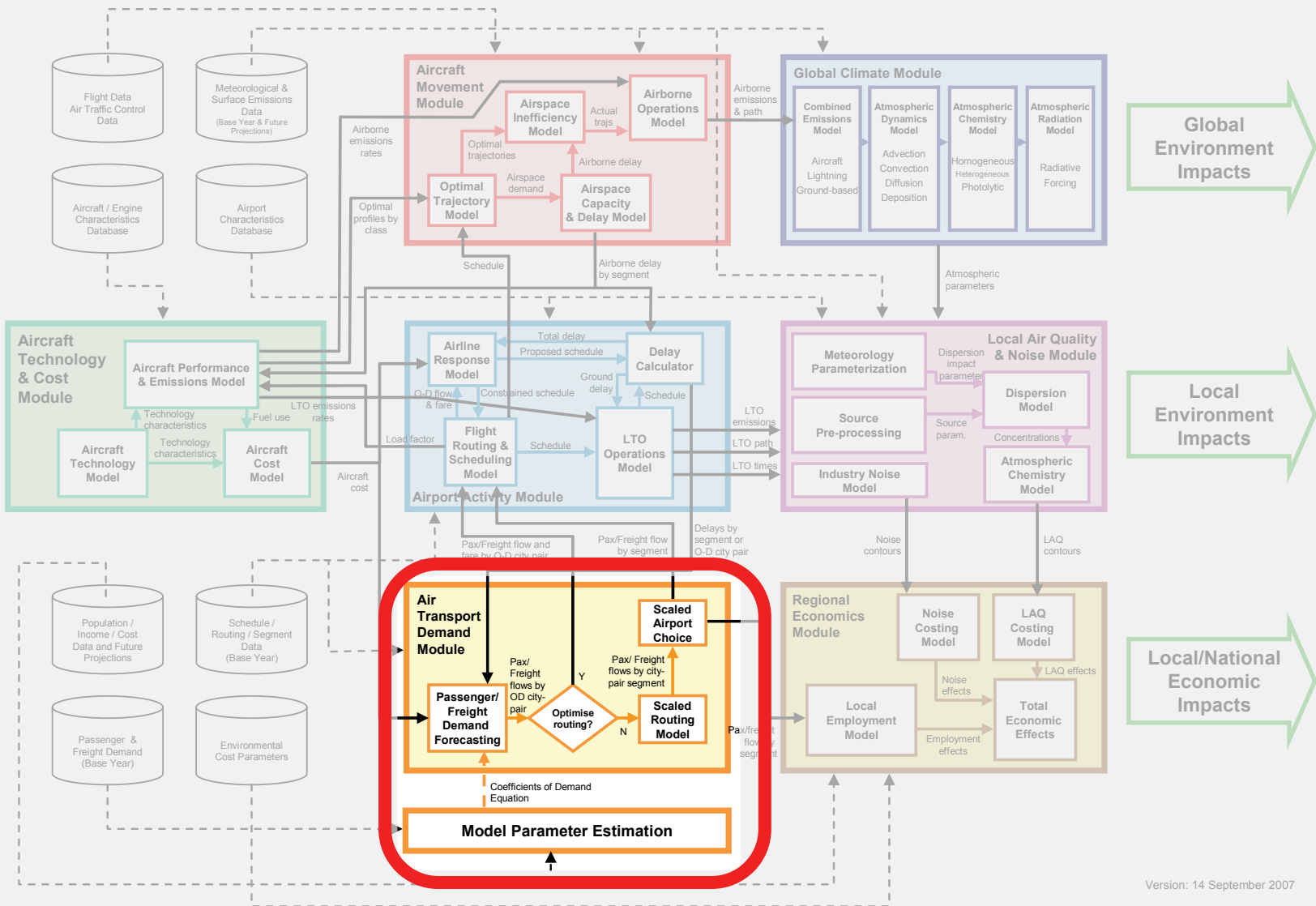
- Natural expansion in sophistication or number of modules

- **Policy assessment potential**



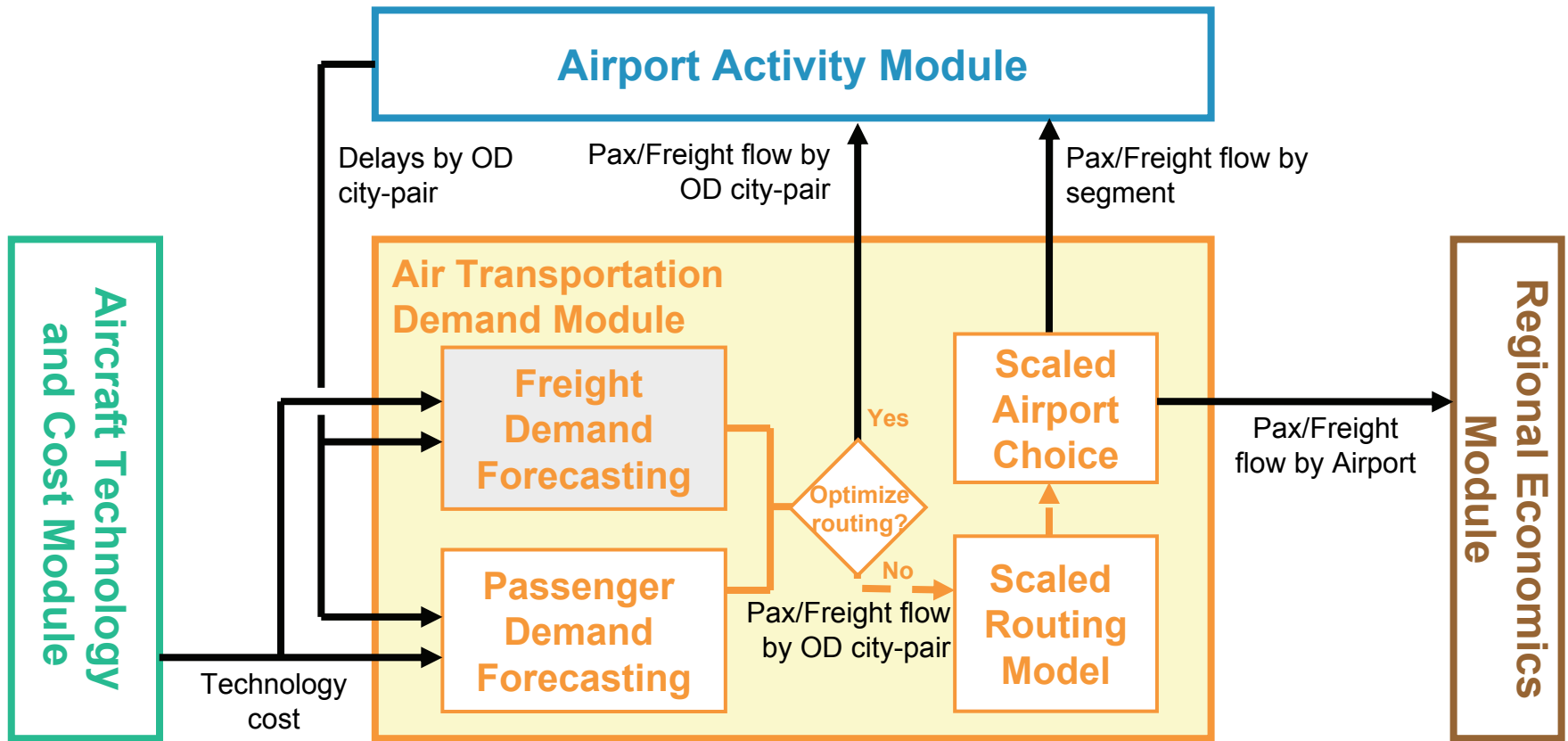
AIM Detailed Architecture





Version: 14 September 2007

- Goal:** Forecast future passenger & freight demand for air travel between global origin-destination city-pairs



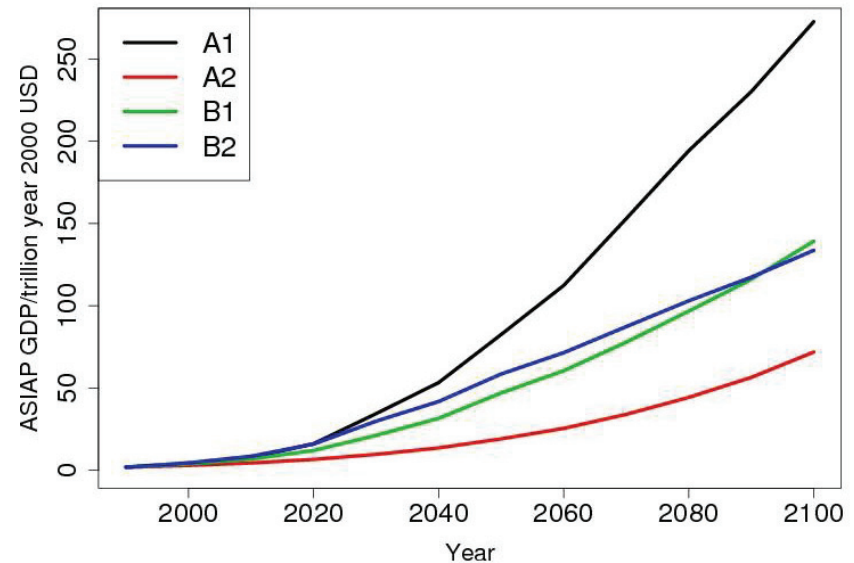
- Base model is a simple one-equation gravity model calibrated against available demand data.
 - Explanatory variables preferably available for as much of the world as possible.
 - Need to have plausible scenarios for development over 50+ years.

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

- Short-, medium- and long-haul estimated separately (future extension to business and leisure demand)
- Insert more complex models for regions where we have more data.
 - Modular structure means that alternative demand models from other groups can also be substituted where appropriate.
- Currently developing methodologies to extend analysis to parts of the world for which data is less readily available.

CURRENTLY:

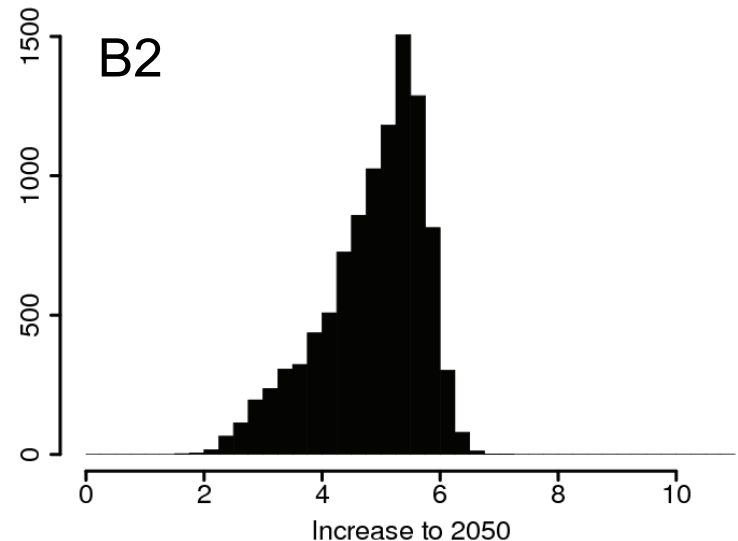
- Integrated model including demand module is functional for US case study (covering ~20% of world air traffic)
- Forecasts of population/GDP growth are taken from the IPCC SRES scenarios.
 - ❑ Allows integration with climate model assumptions.
 - ❑ Forecast horizon needs to be chosen carefully.
- Uncertainty in input parameters is unavoidable – needs to be followed through the rest of the program.

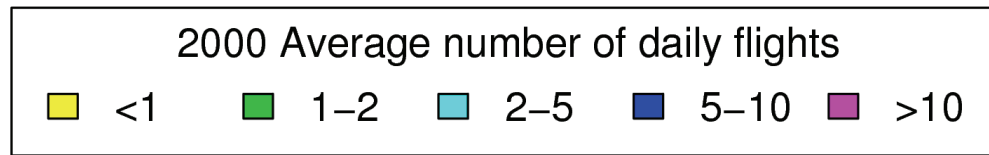
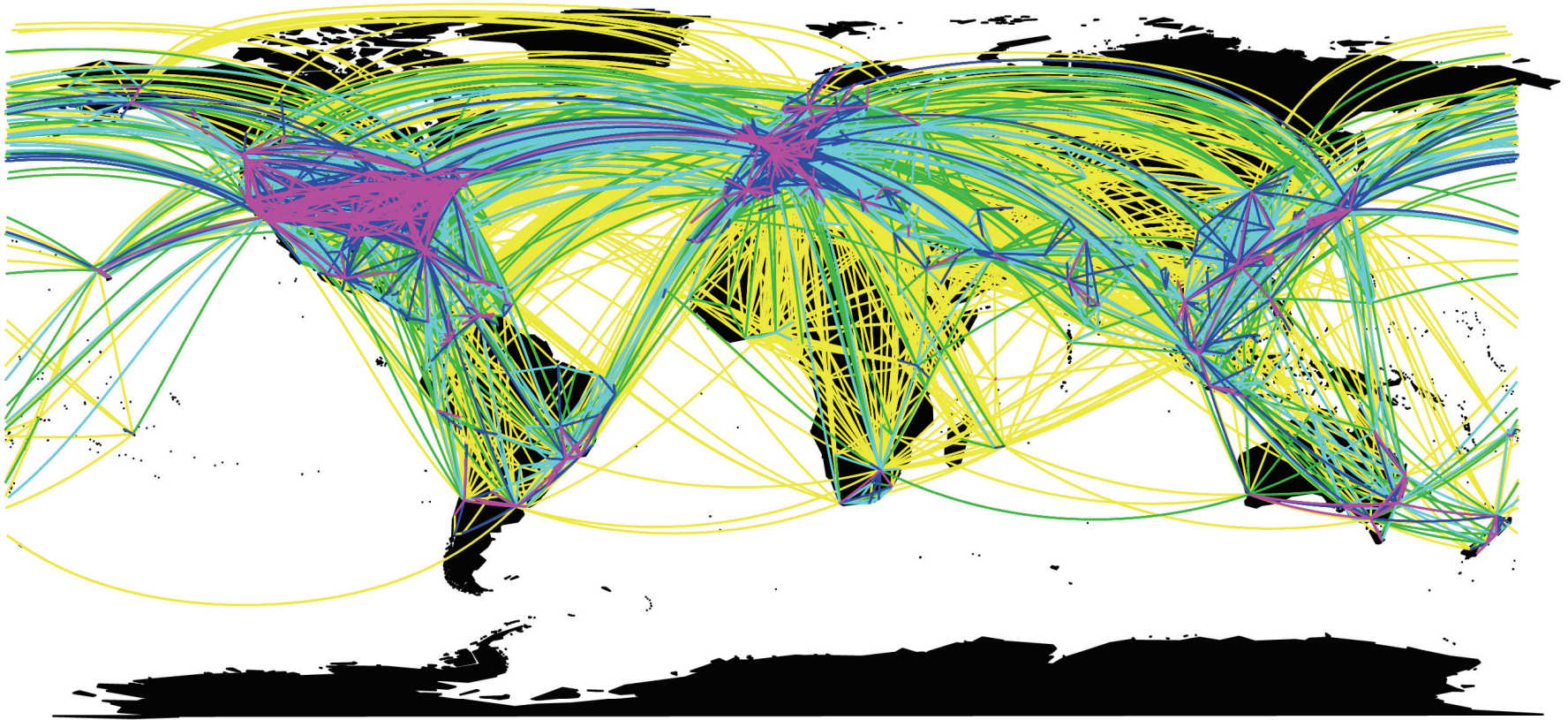


[Source: IPCC SRES]

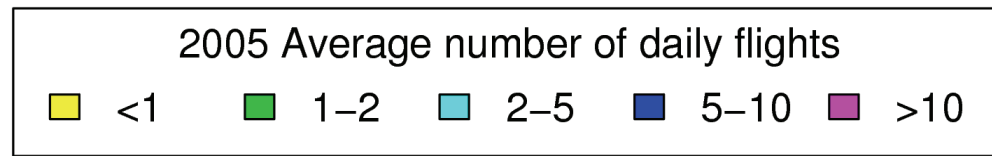
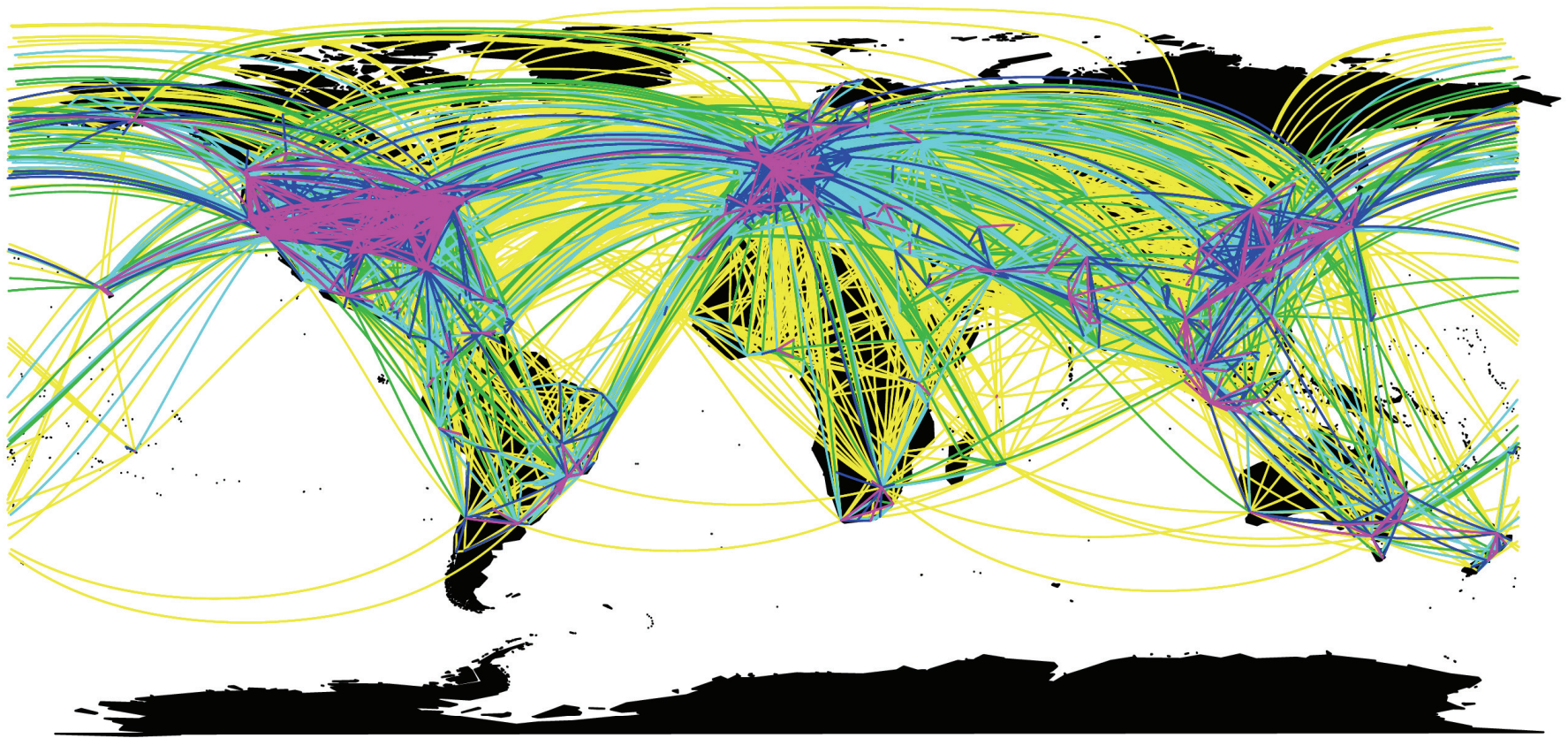
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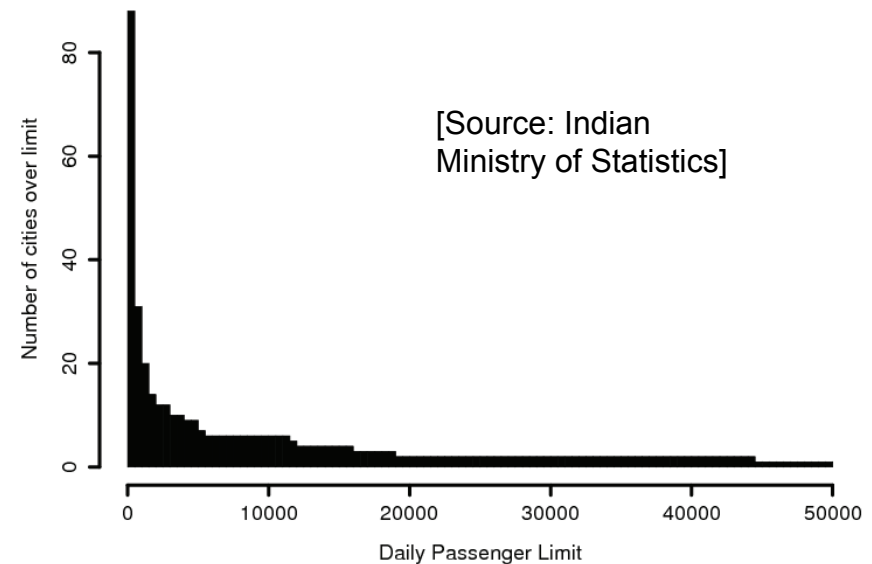
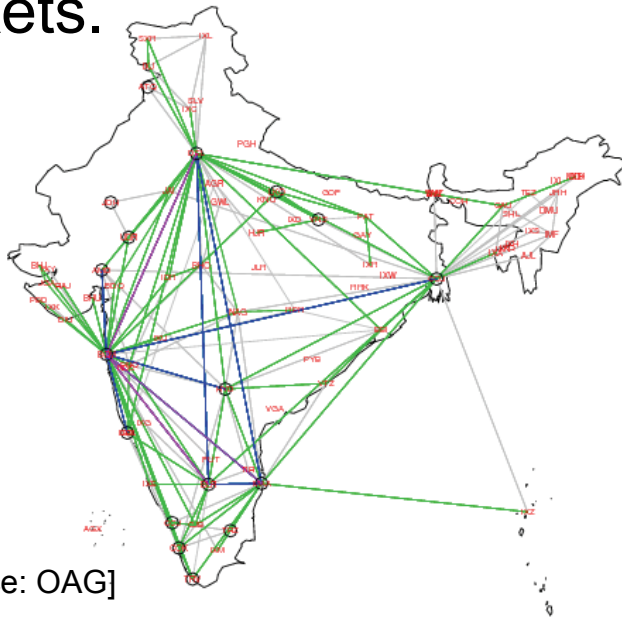


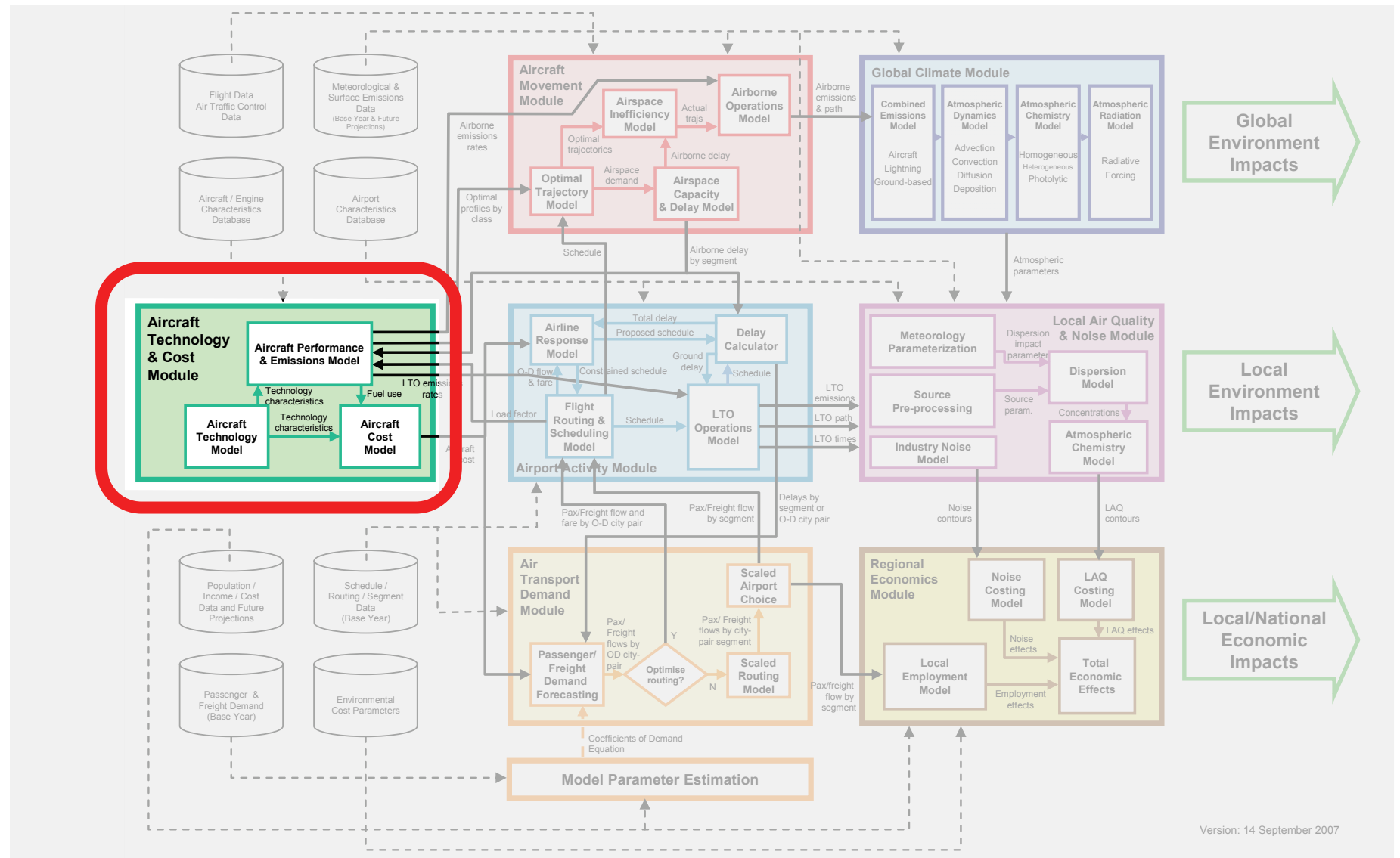
[Source: OAG]



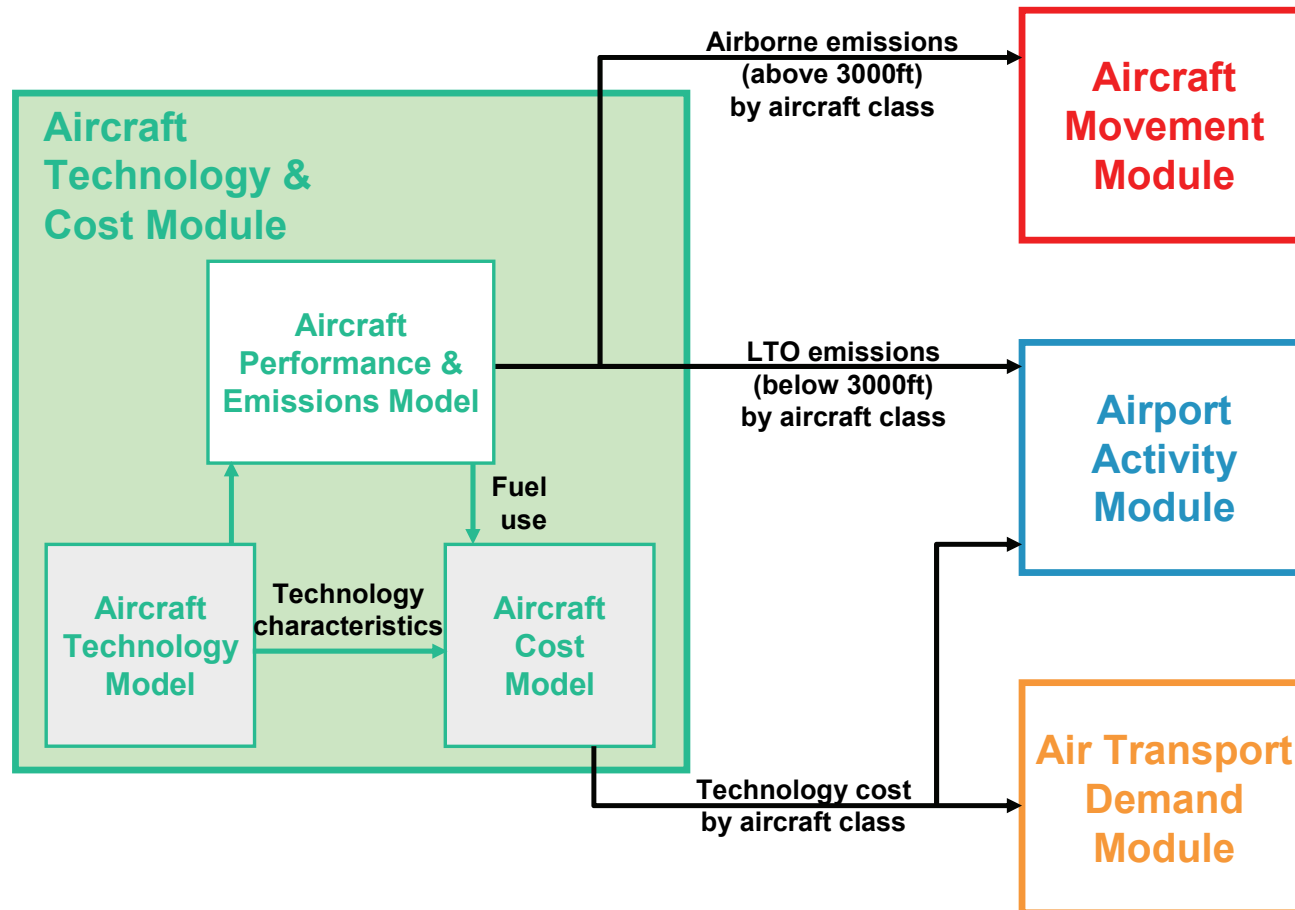
[Source: OAG]

- Current detailed case studies focus on mature markets.
 - Data availability
 - Ability to compare predictions with other models
- Robustness of world model would be greatly improved by having more detailed case studies of rapidly-developing markets.





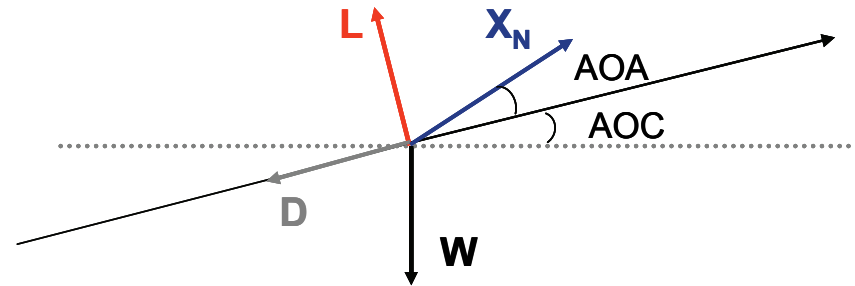
- **Goal:** Model aircraft performance, fuel use, emissions and operating costs for different technologies



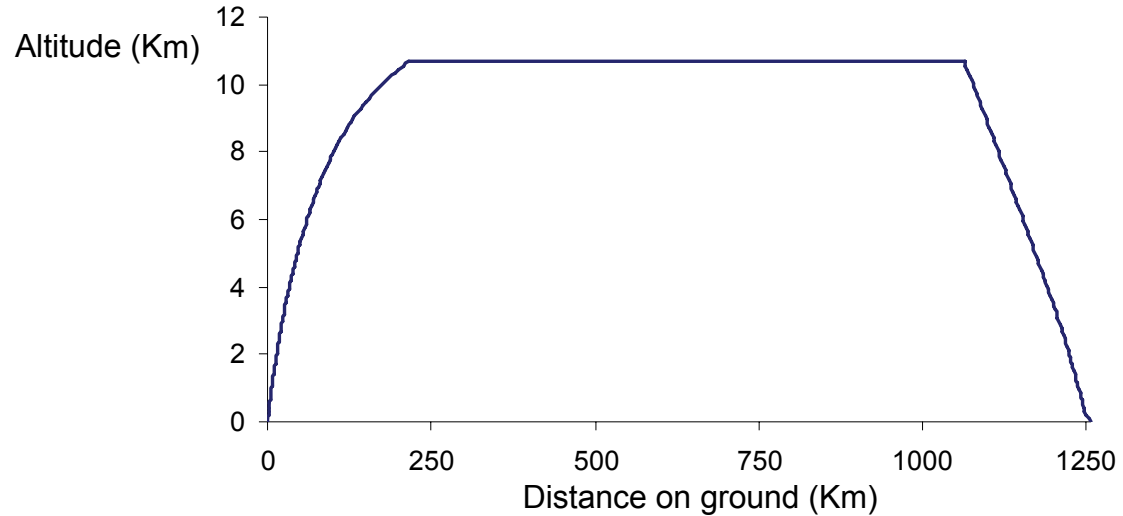
- EUROCONTROL Base of Aircraft Data (BADA)

$$\frac{dh}{dt} = \left[\frac{(T - D)V_{TAS}}{mg} \right] f \{ M \}$$

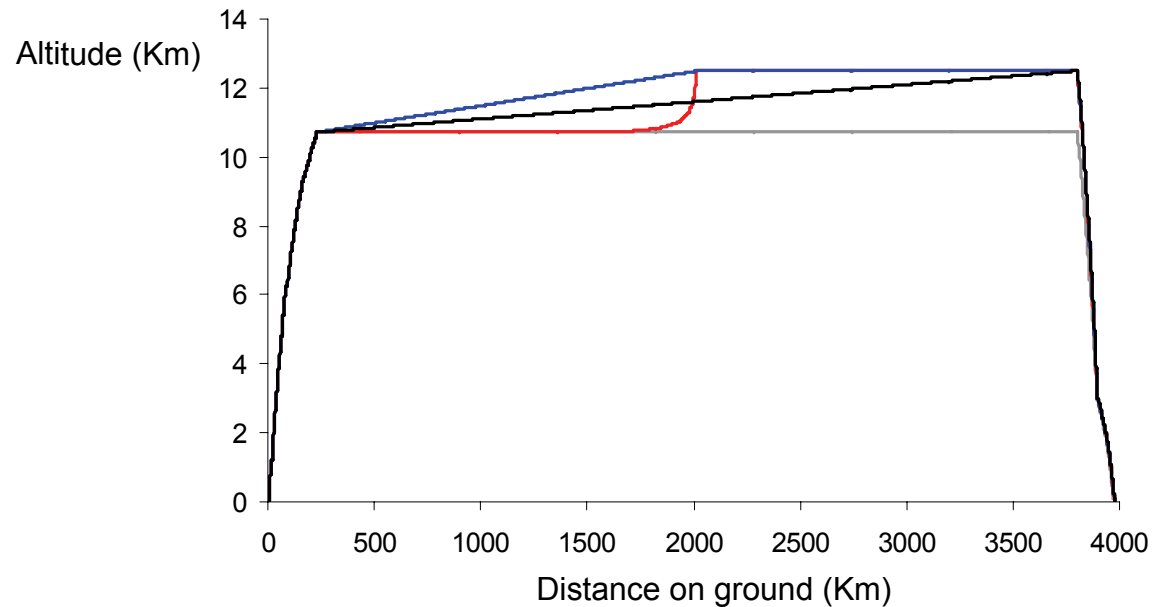
- ❑ Simple model
 - ❑ Data for a large number of aircrafts
 - ❑ Constrained to standard flight missions
 - ❑ No control/degree of freedom
 - ❑ Engine cycle not simulated
- PESO under development
 - ❑ More complex model
 - ❑ Engine simulated using GasTurb
 - ❑ Highly flexible
 - ❑ Can be used to identify which new technologies are viable



B737-800
Short-Haul
trajectory
modelled with
BADA



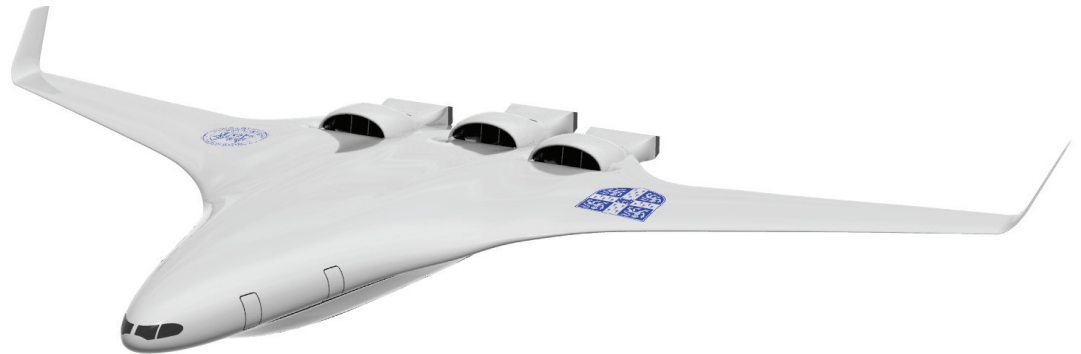
B737-800
Medium-Haul
trajectory
modelled with
PESO



- Model future aircraft technologies



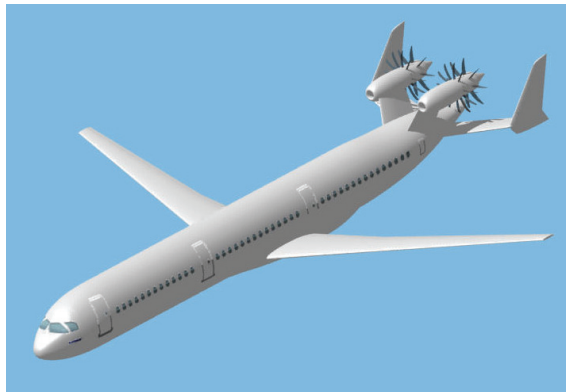
Very Light Jets



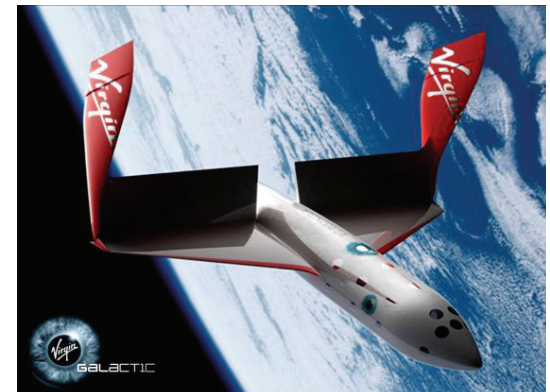
Blended Wing Bodies (SAI)



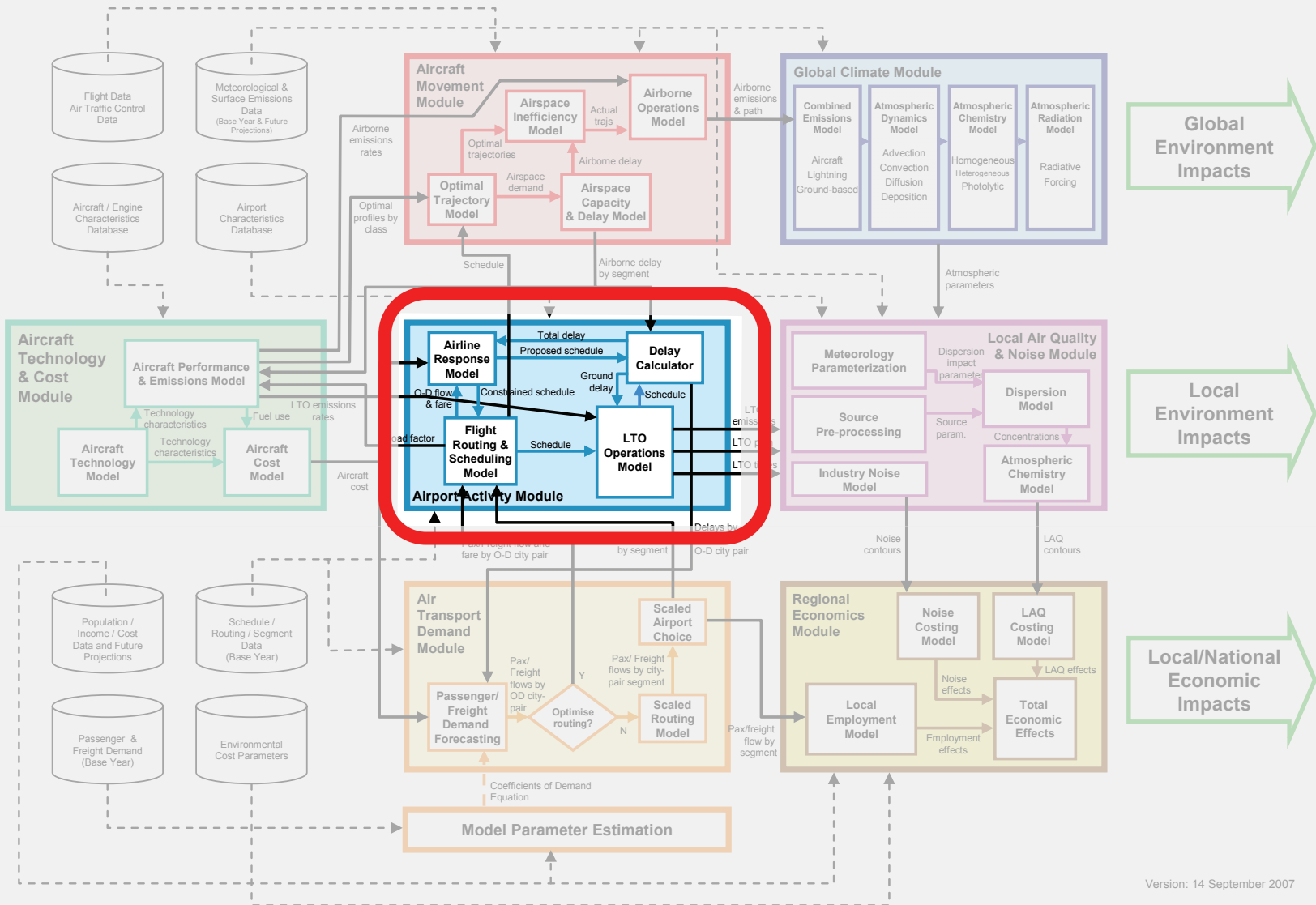
Supersonic Business Jets



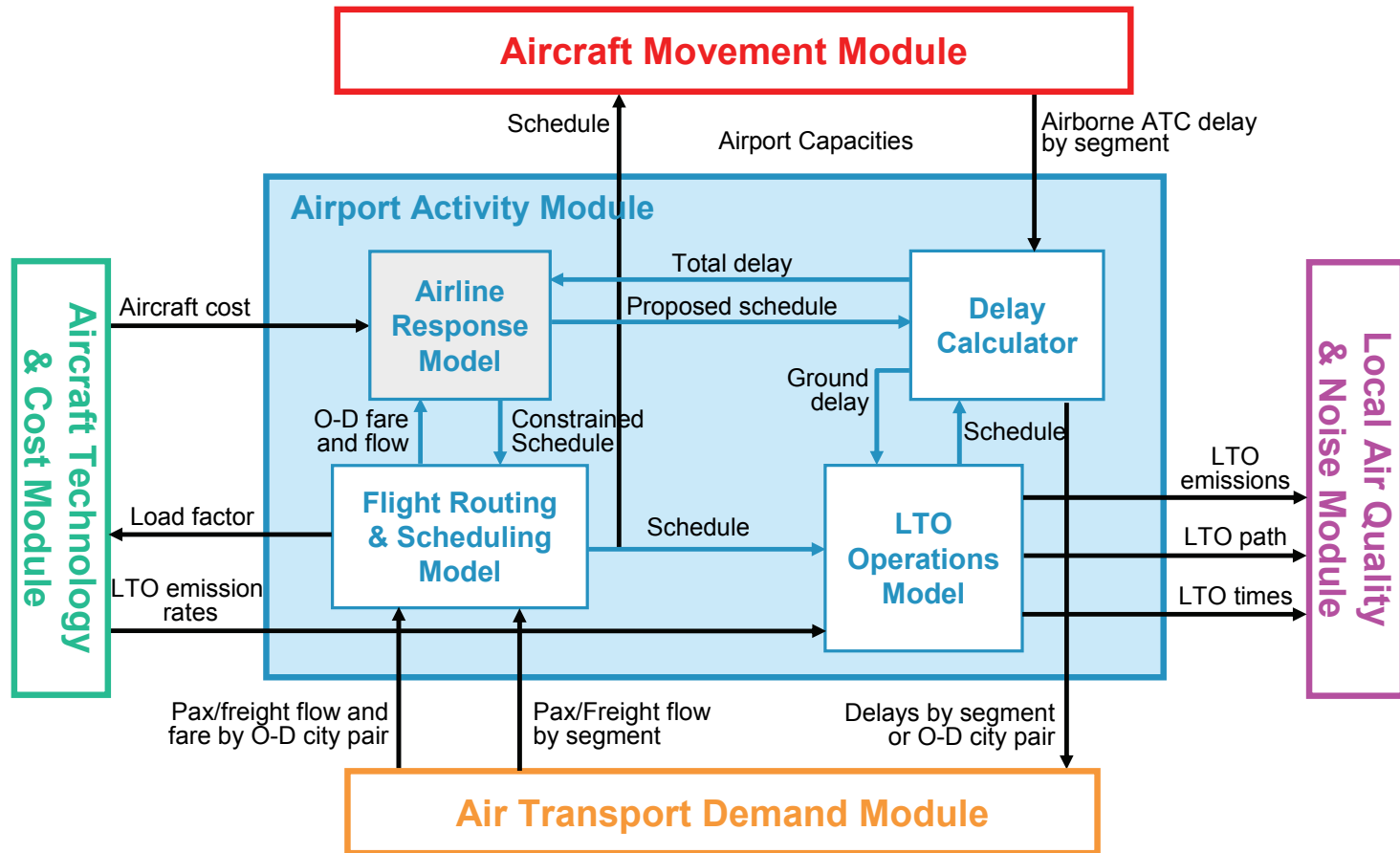
Open rotor configuration (ACROPOLIS, EU)



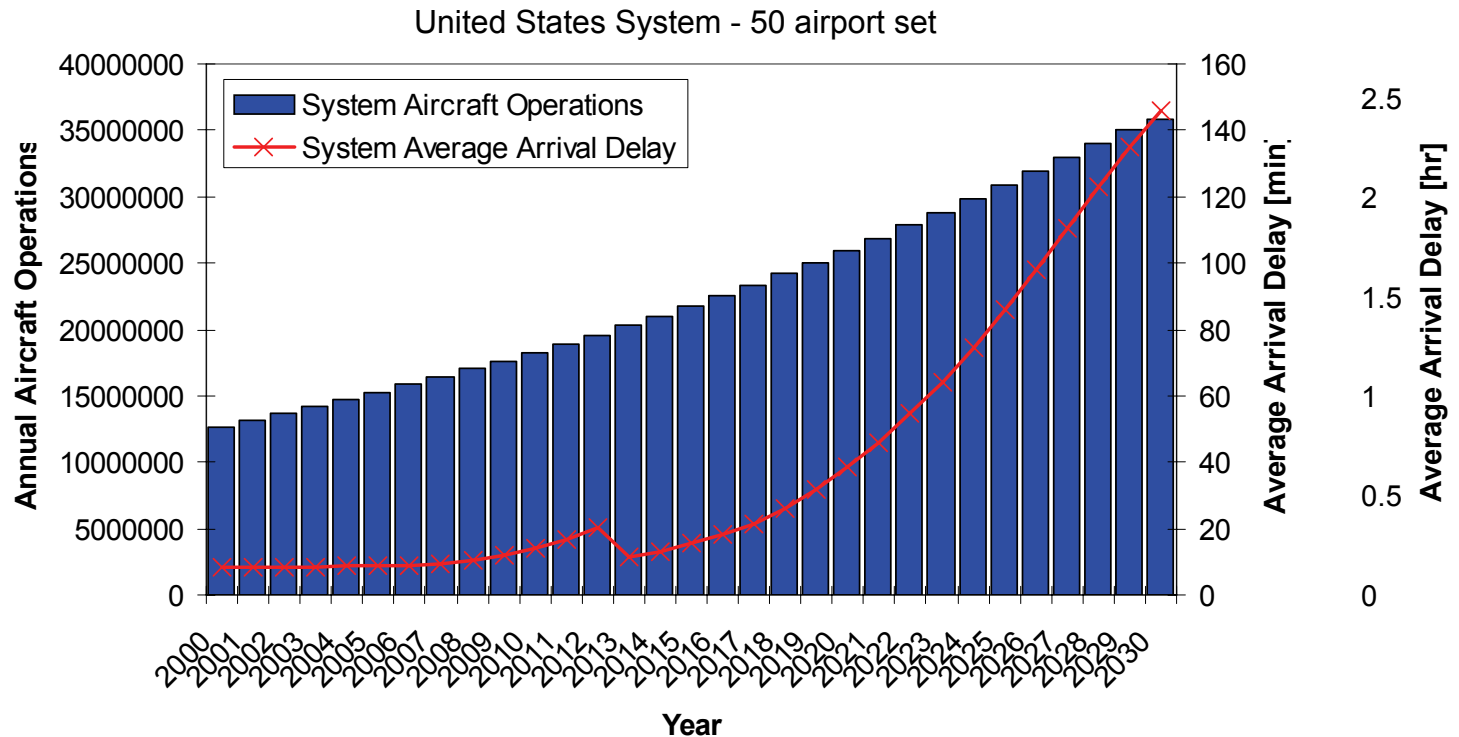
Virgin Galactic



- Goals:** Forecast air traffic growth as function of demand; and airport operations/congestion as function of air traffic



- Results from forecasting US air traffic growth to 2030 based only on historical trends in traffic growth:



- Forecast delays highly unrealistic
 - Requires modelling of airline response to delays

CURRENTLY

- Base year routing network applied for all forecasts
- Flight frequency scaled from segmented passenger demand according to base year load factors, by segment
- Aircraft size distribution calculated according to multi-variate regression on base year data

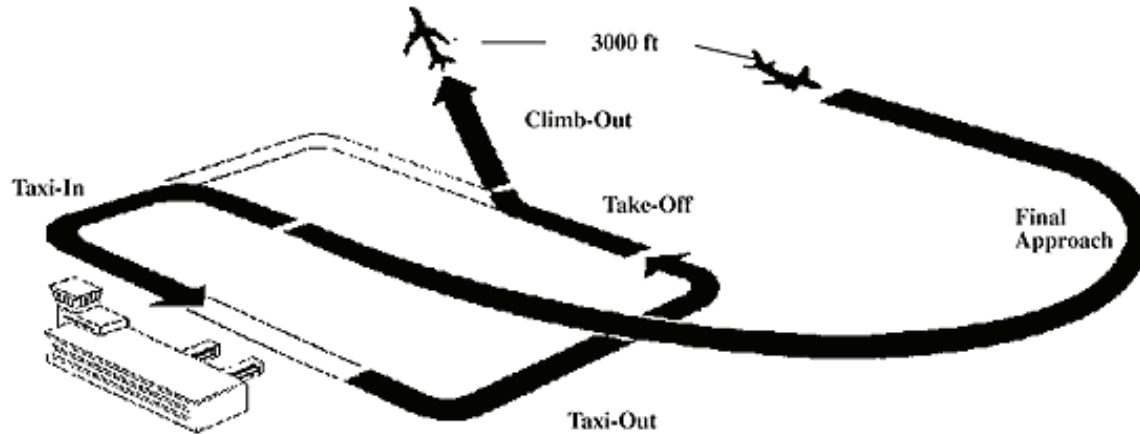
$$P_i(y_i = j | x_i, \beta) = \alpha_{ij} + \beta_1(Pax/Freight\ demand) + \beta_2(Stage\ length) \\ + \beta_3(Origin\ hub\ dummy) + \beta_4(Destination\ hub\ dummy)$$

For $j = 1, \dots, 3$

- No airline response to increasing delays modelled

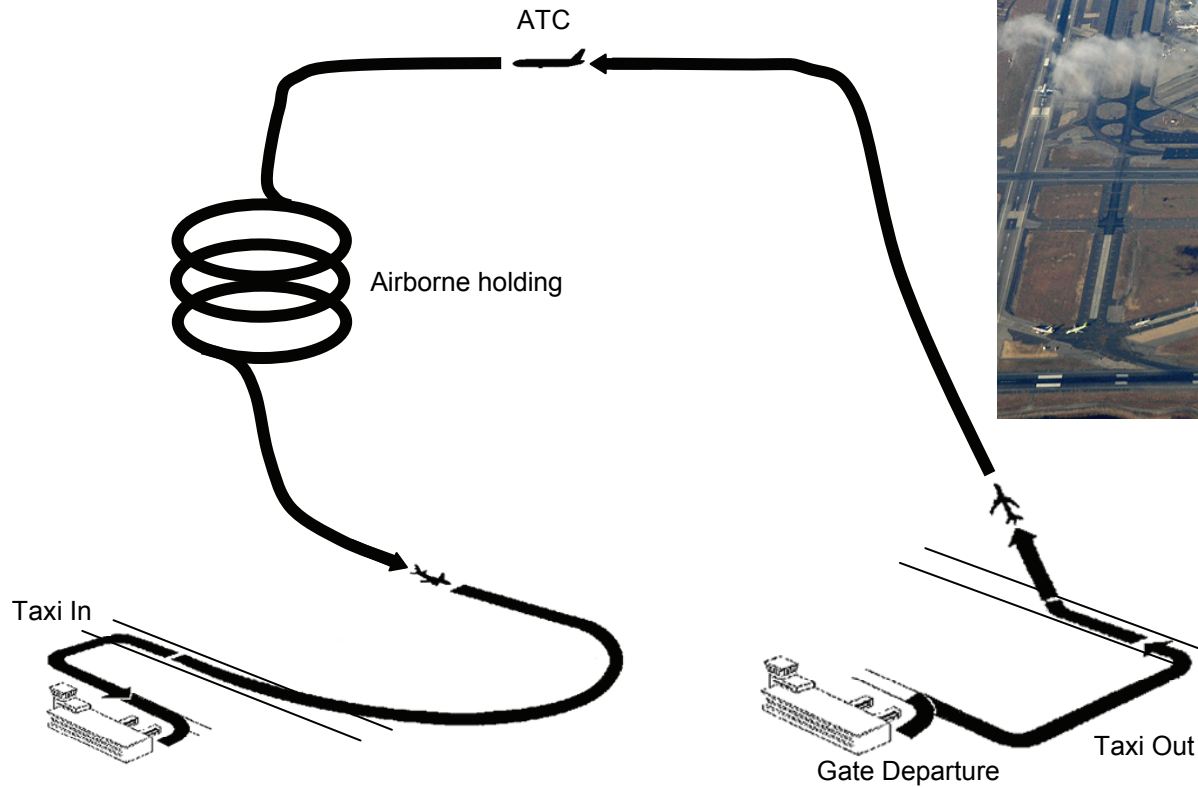
DEVELOPMENT

- Include modelling of airline response to flight delays



- Estimate emissions from taxi-out, take-off, climb-out, final approach, landing, & taxi-in
 - ❑ LTO emissions have a direct impact on Local Air Quality
 - NO_x , $\text{PM}_{2.5}$
 - ❑ Taxi emissions impacted by delays at congested airports
 - ❑ Detailed delay modelling required
- Delays also affect airline costs and passenger travel time

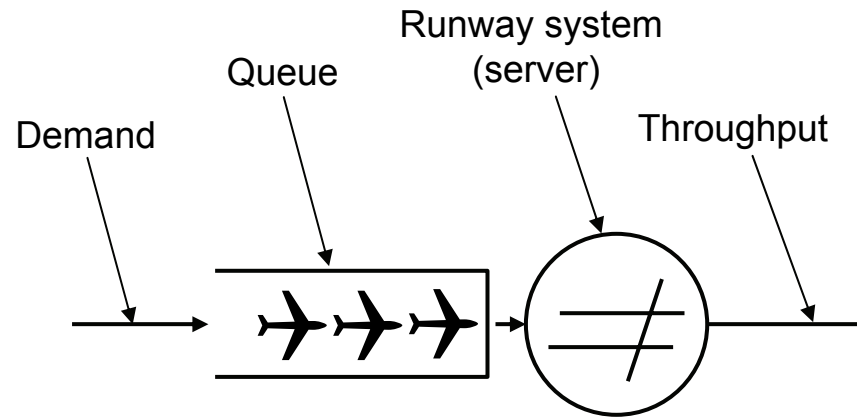
Figure from IPCC Report on Aviation and the Global Atmosphere, 1999



$$\bar{D}_{Arrival}^{i,j} = \bar{D}_{Gate}^i + \bar{D}_{Taxi\ Out}^i + \bar{D}_{Airborne\ ATC}^{i,j} + \bar{D}_{Airborne\ Holding}^{i,j} + \bar{D}_{Taxi\ in}^j$$

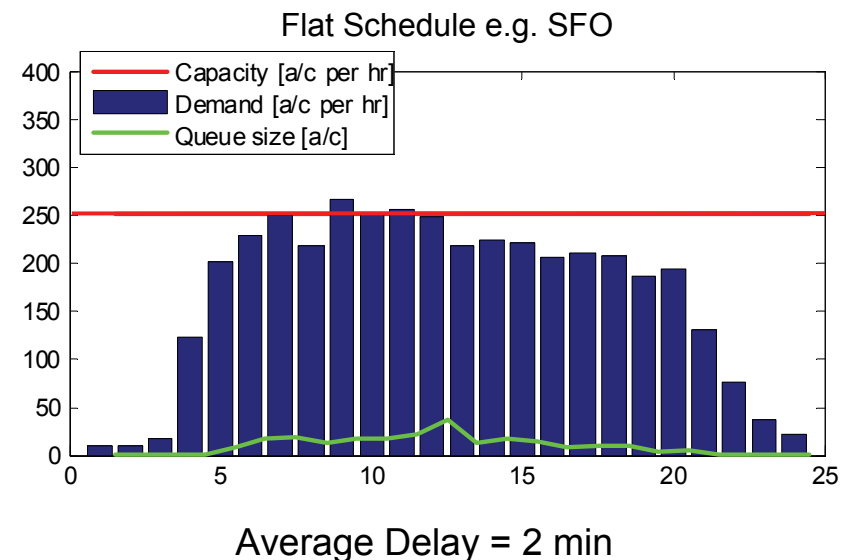
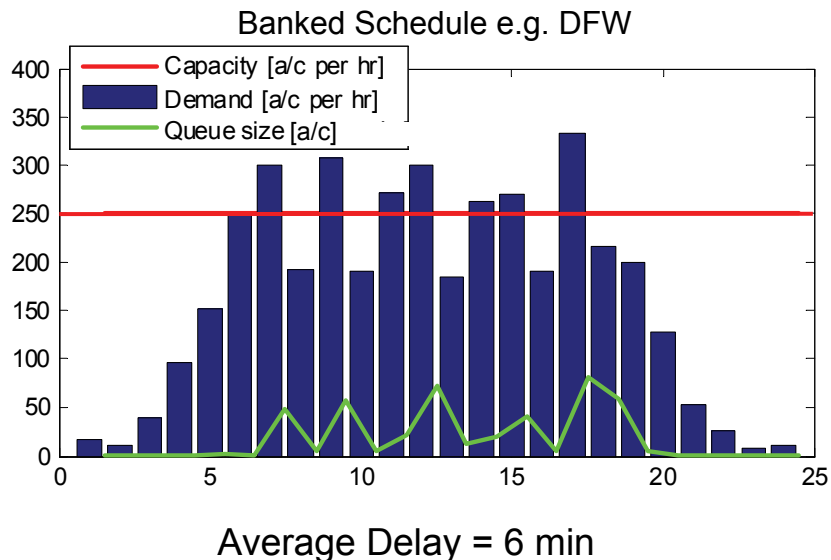
Figure developed from figure in IPCC Report on Aviation and the Global Atmosphere, 1999

- Runways typically primary bottleneck in system
- Delays resulting from airport capacity constraints modelled applying queuing theory



- Data requirements:
 - ❑ Airport capacities (aircraft per hour)
 - ❑ Delay statistics (average gate, taxi-out, airborne delays)

- Change schedule to flatten highly banked schedules to lower delays
 - ❑ Flatten schedules as delay approaches and exceeds an estimated delay threshold



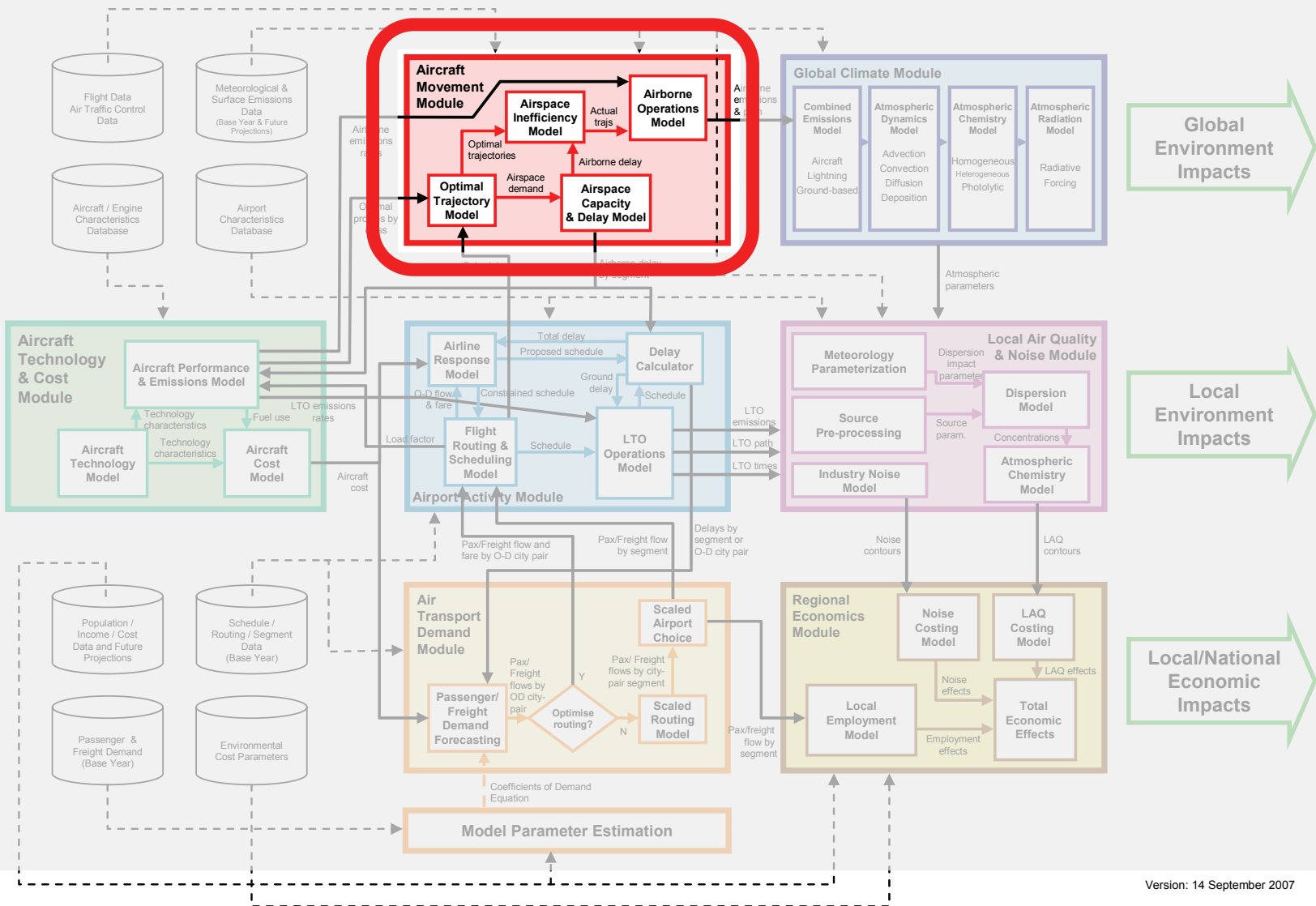
- Increase aircraft size
 - ❑ Increase proportion of larger aircraft types operated as delay approaches and exceeds an estimated delay threshold

- Change routing network to avoid delays
 - Avoid congested hubs
 - Operate new hubs
 - Use secondary airports
- Routing Optimisation
 - Design routing and aggregate scheduling to maximise airline operating profit

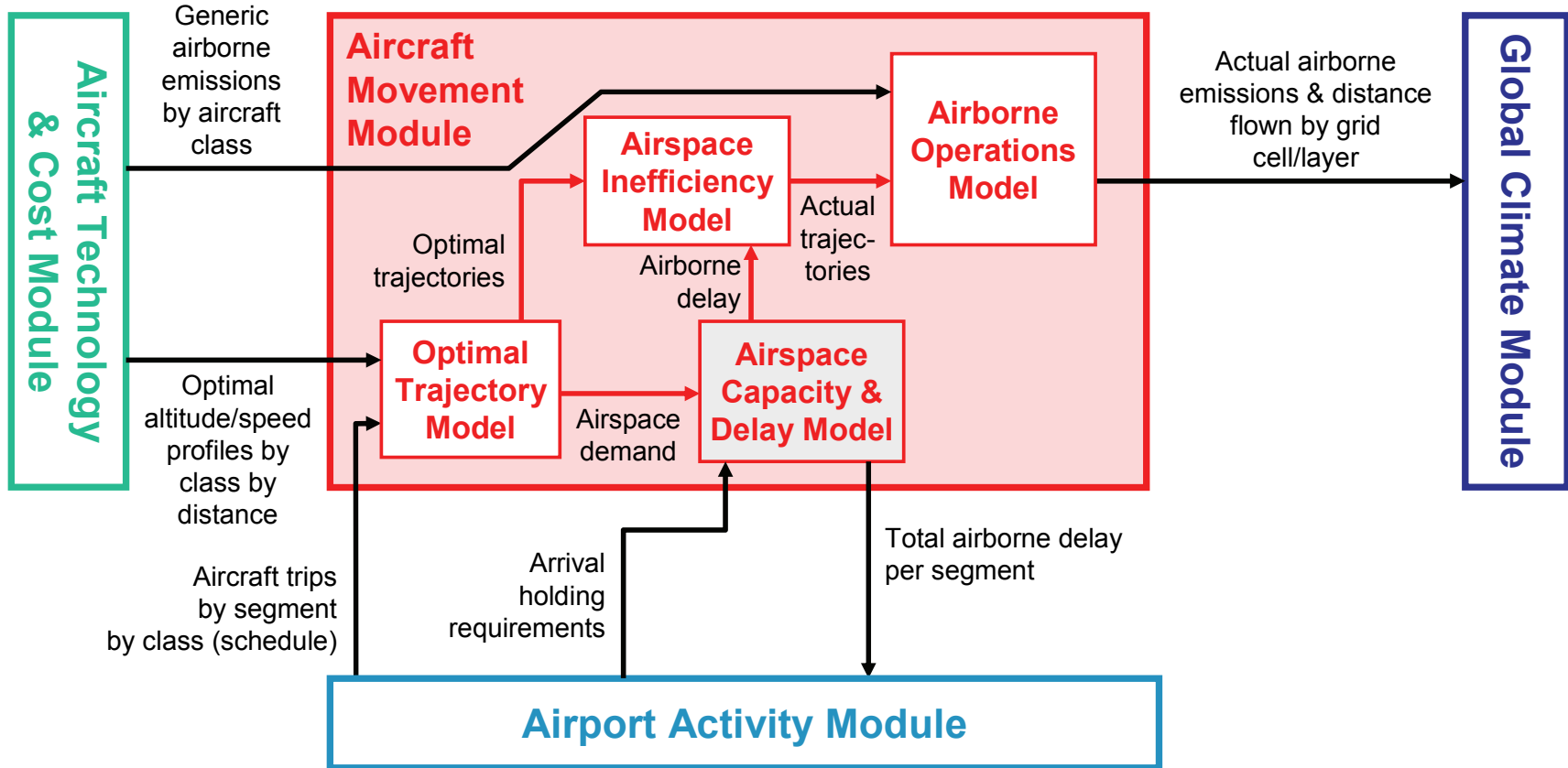
$$\max \left(\sum_{i,j} \sum_{p \in P_{i,j}} \text{Fare}_{i,j}^p \cdot \text{Pax}_{i,j}^p - \sum_{m,n,k} \text{OpCost}_{m,n,k} \cdot \text{FltFreq}_{m,n,k} \right)$$

- O/D passenger demand a function of travel time, which is a function of delay, which is a function of flight frequency
 - Solution requires iteration through Demand Module and Delay model
- Operating Cost a function of travel time, and thus delay
 - Solution requires iteration through Delay model

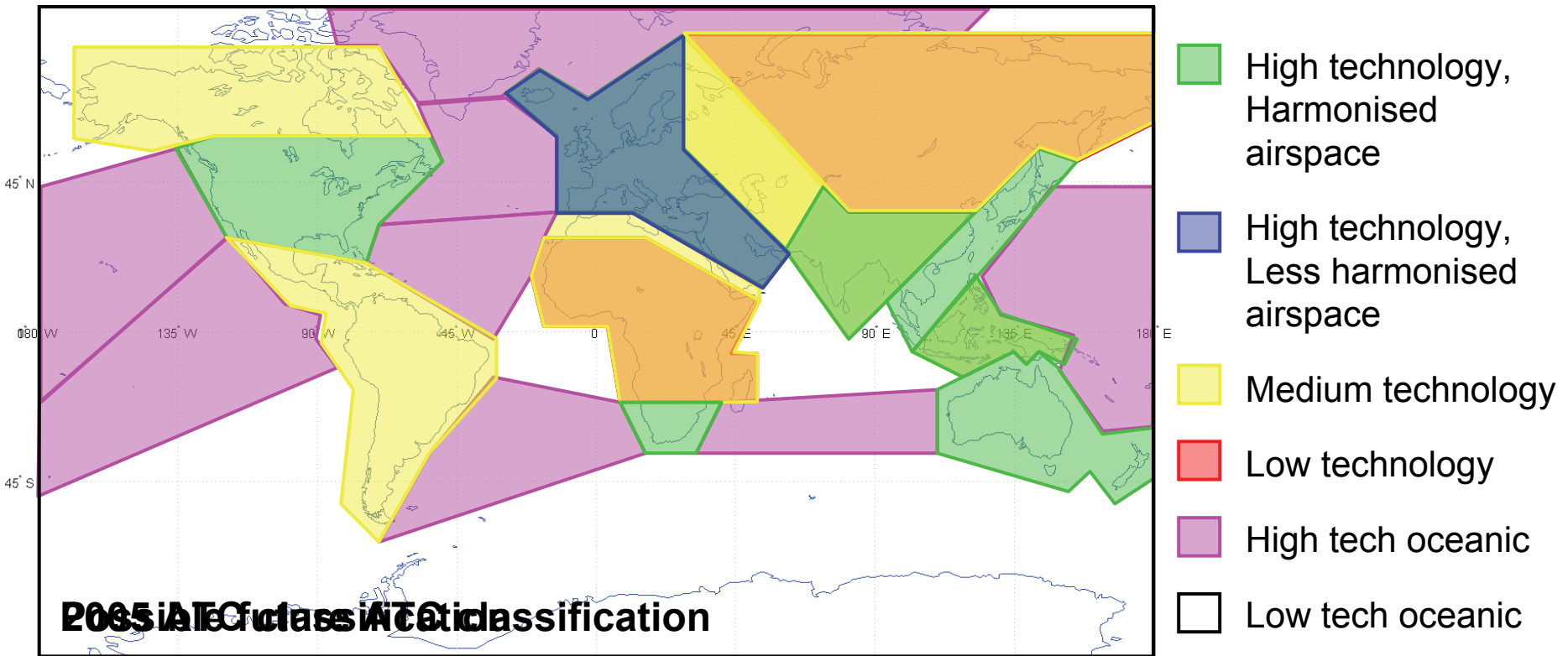
AIM Detailed Architecture

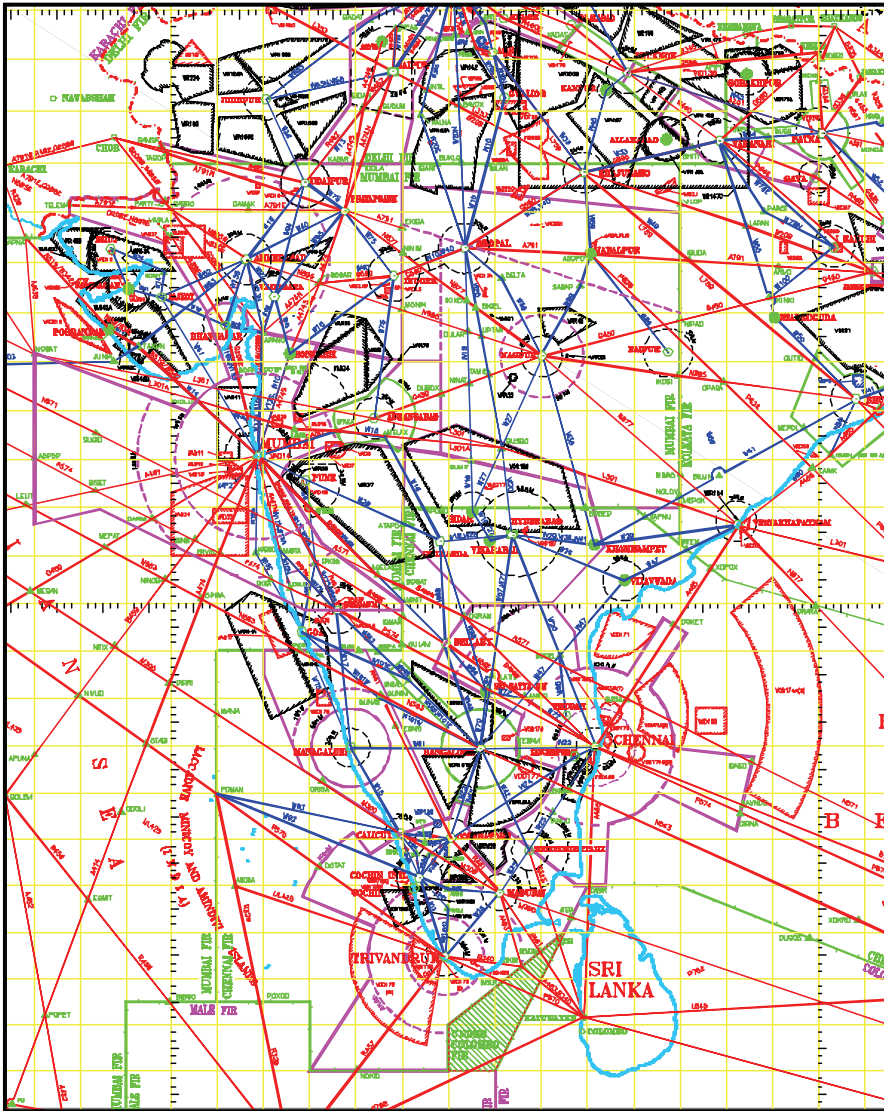


- Goals:** Identify location of emissions released from aircraft in flight; Predict airborne delay characteristics

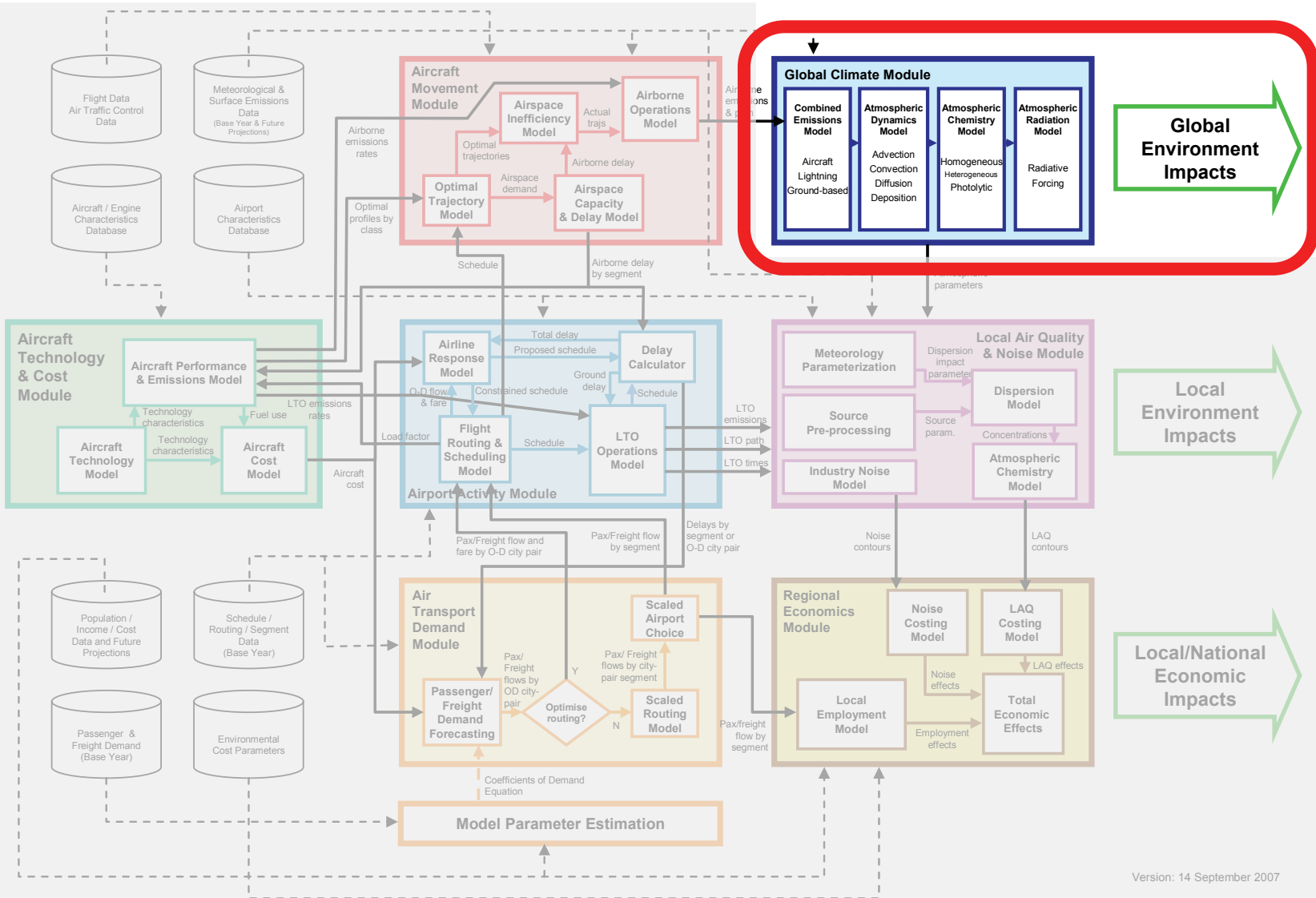


- Optimal trajectories degraded by “real world” inefficiency factors
 - Airspace route structures; Restrictions (military areas, convective weather); Conflict avoidance (separation minima); Delay
- Inefficiency factors defined for different world regions, now and in future

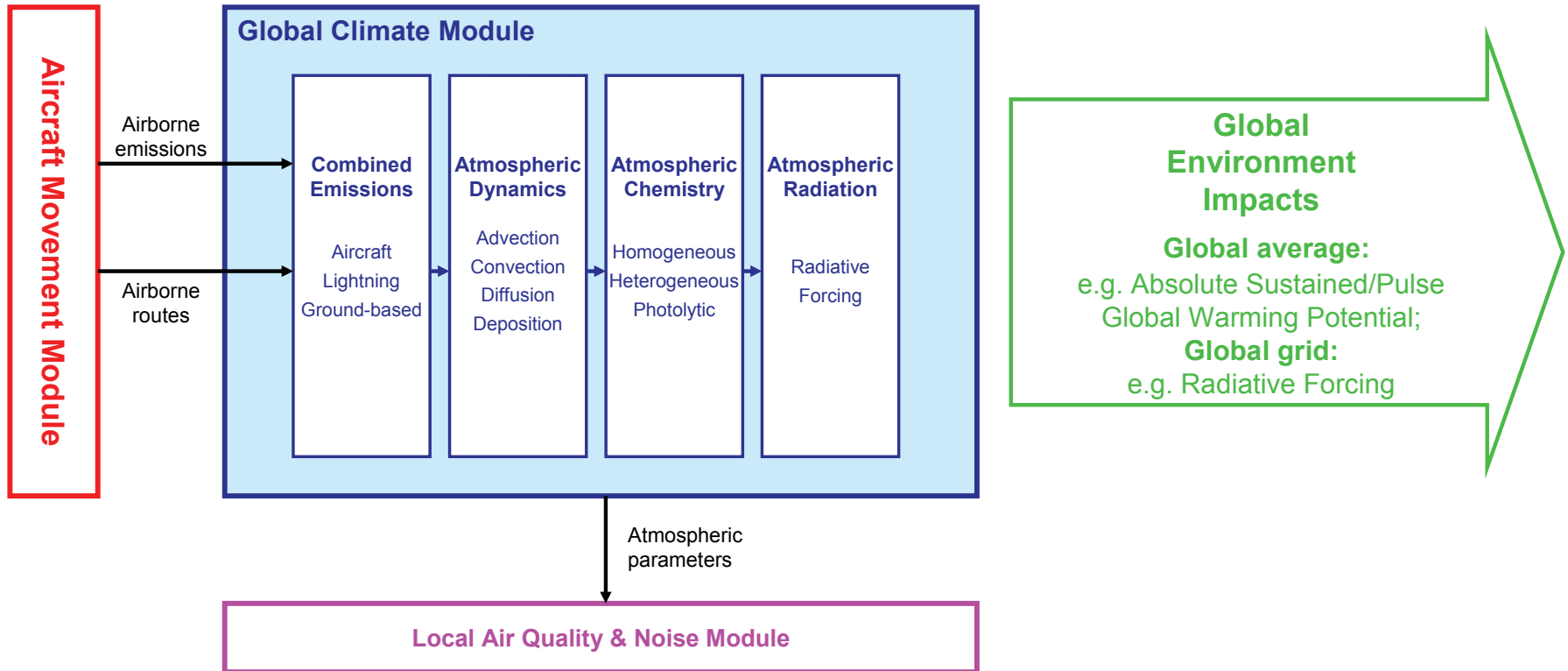




- Need lateral and vertical inefficiency factors for airspace: ideally past, present and future predictions
- Published or data driven
 - Radar data giving lat, long, alt, speed, aircraft type
- If data unavailable, need understanding of infrastructure technology level, restricted areas, etc., now and in future



- Goals:** Determine impact of aircraft emissions on the global climate system (CO_2 , NO_x , SO_x , H_2O)



Configuration 1

Global Climate Model

General Circulation Model

Calculates meteorological data – particularly suitable for realistic future climate simulations

Chemistry Module

Whole-atmosphere chemistry, useful for subsonic or supersonic aircraft fleet

Radiation Module

Built-in radiation scheme allows feedback on chemistry & transport

Configuration 2

Chemistry Transport Model

Forced by actual meteorological analyses – particularly suitable to simulate specific meteorological situations

Primarily aimed at simulating effects from subsonic fleet

Vertical limit 30 km

Flexible grid resolution

Radiation Model

Off-line radiative code to calculate radiative impact

Configuration 3

Parametric Model

Parametric version of Chemistry Transport Model

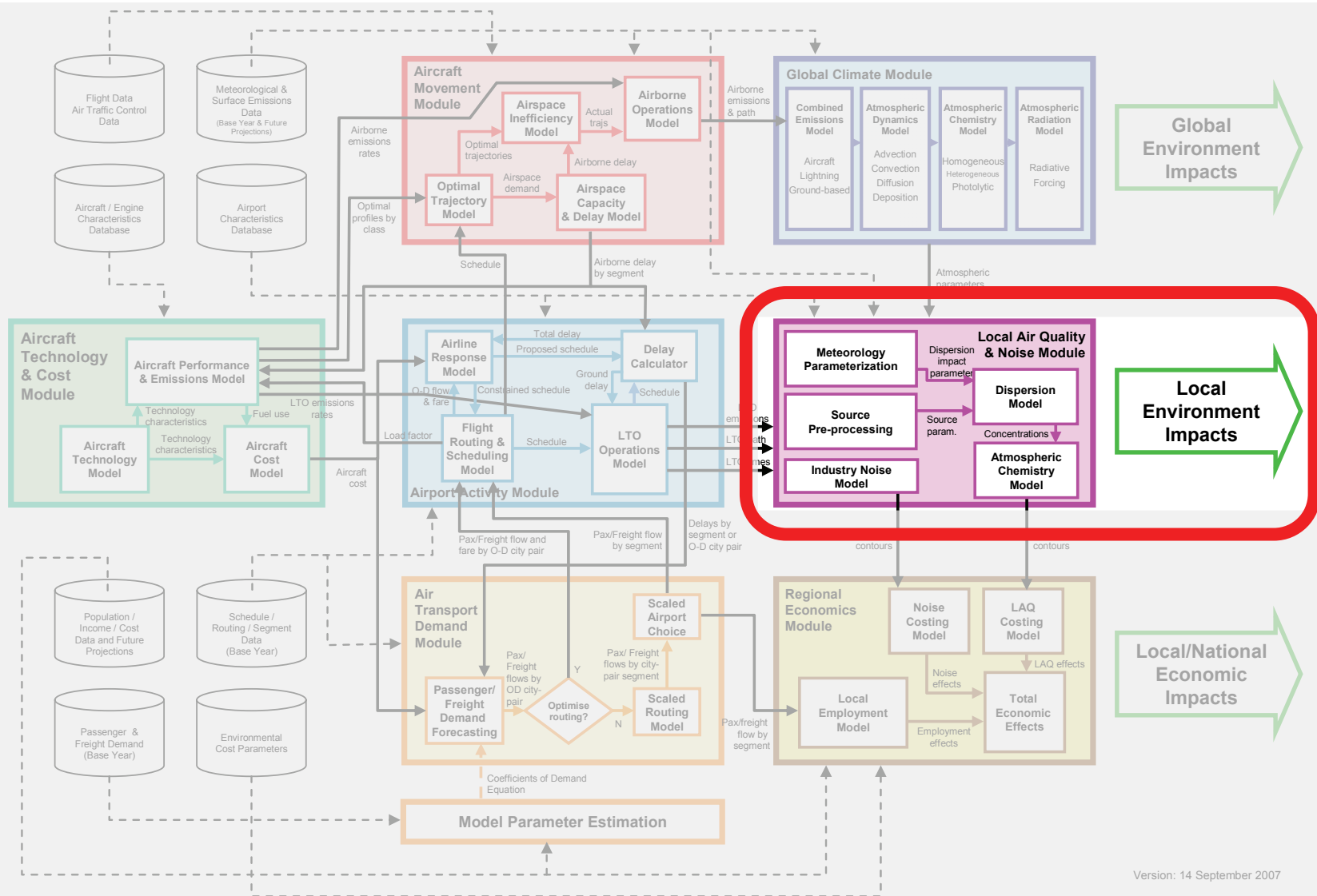
Allows large number of sensitivity studies at low computational costs

Experiments possible within valid range of parameterisation

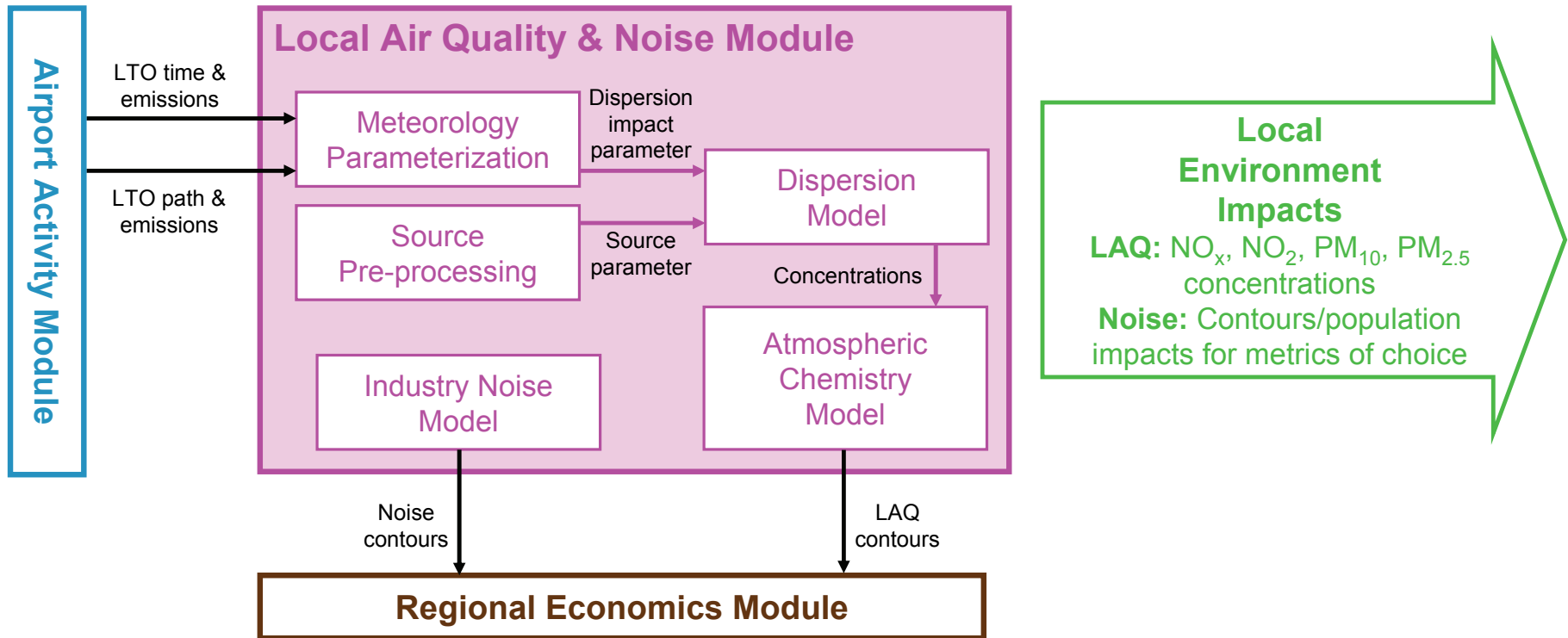
Provides direct output of global climate metric (RF, GWP)

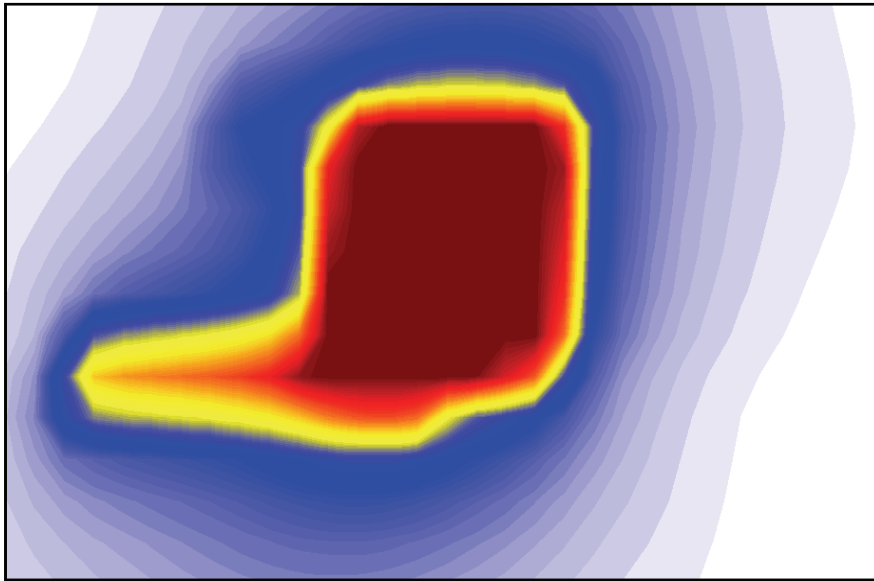
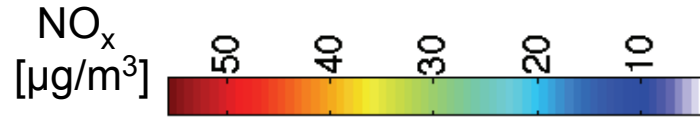
Decreasing Complexity and Run Time





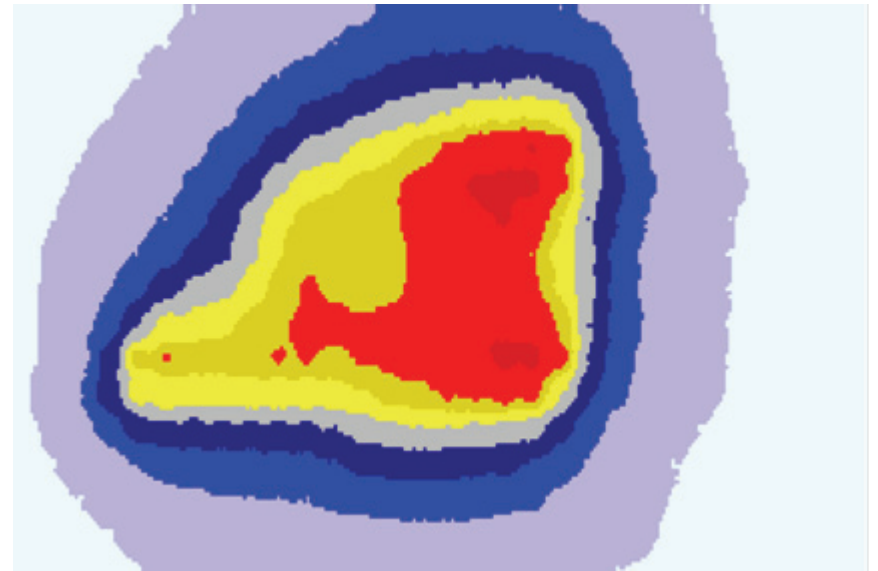
- Goals:** Investigate dispersion of critical pollutants (NO_x , PM, O_3) and noise impacts in airport vicinity





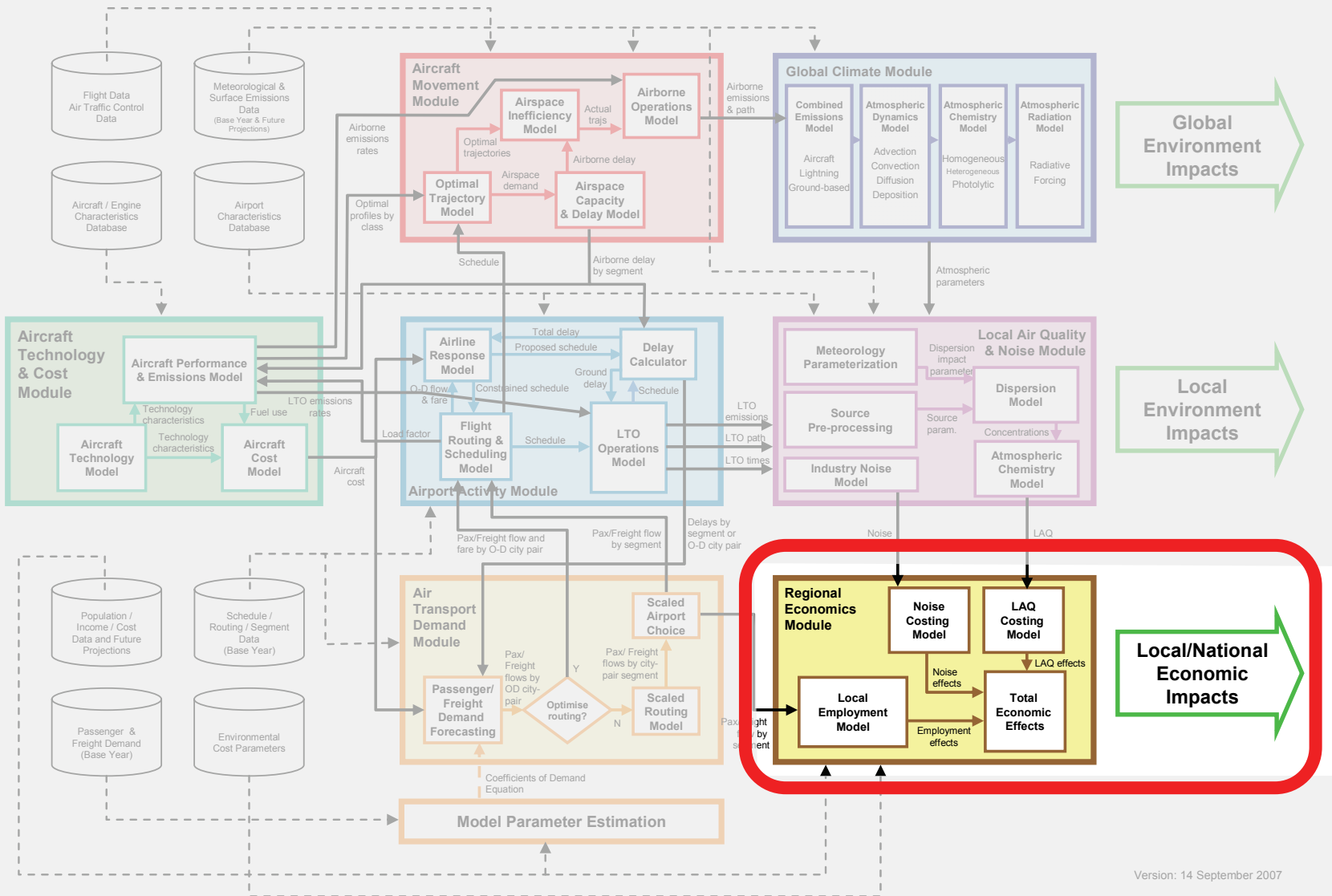
6 km

AIM LAQ Module NO_x result
~10 sec

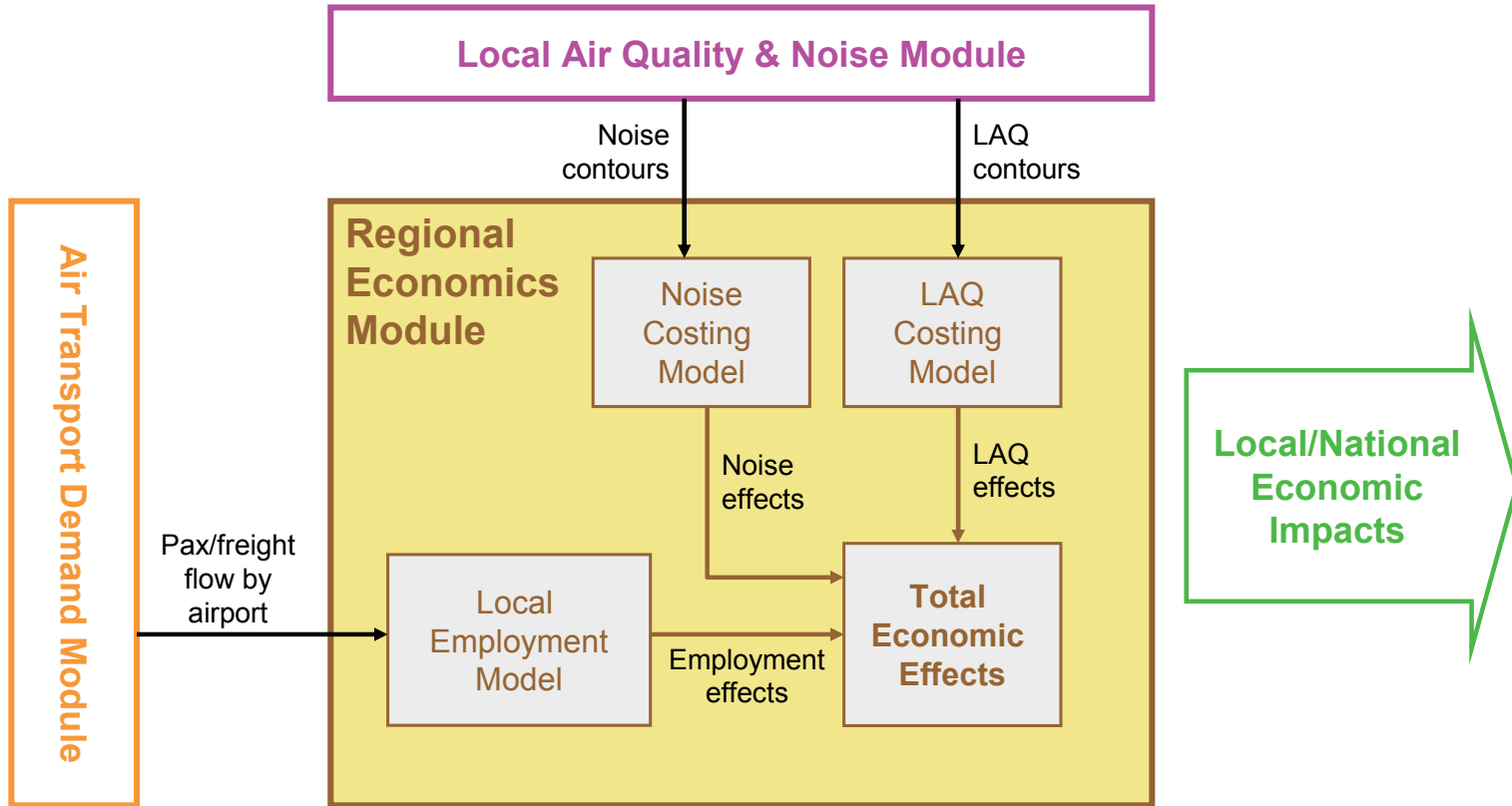


6 km

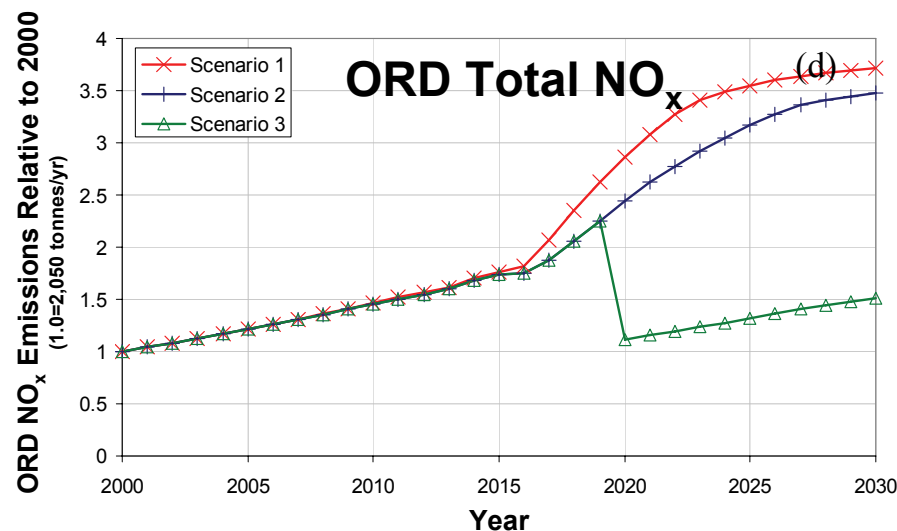
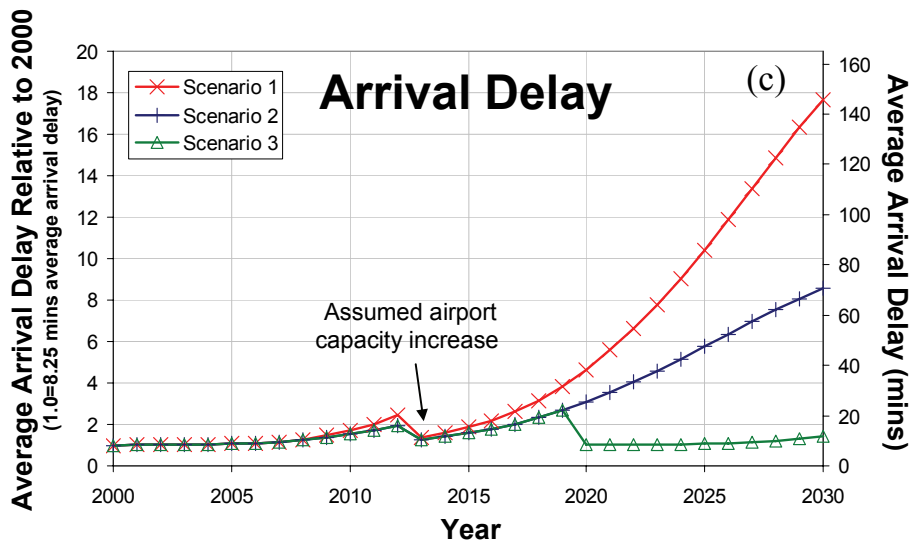
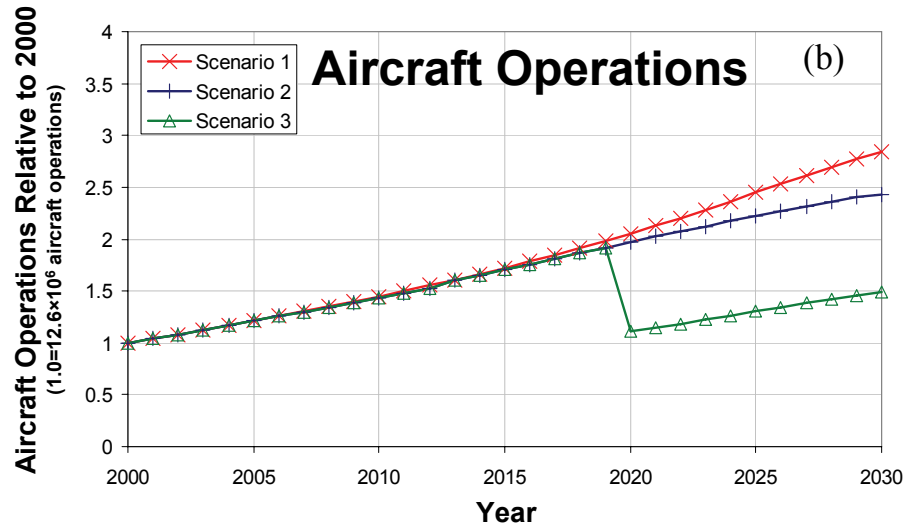
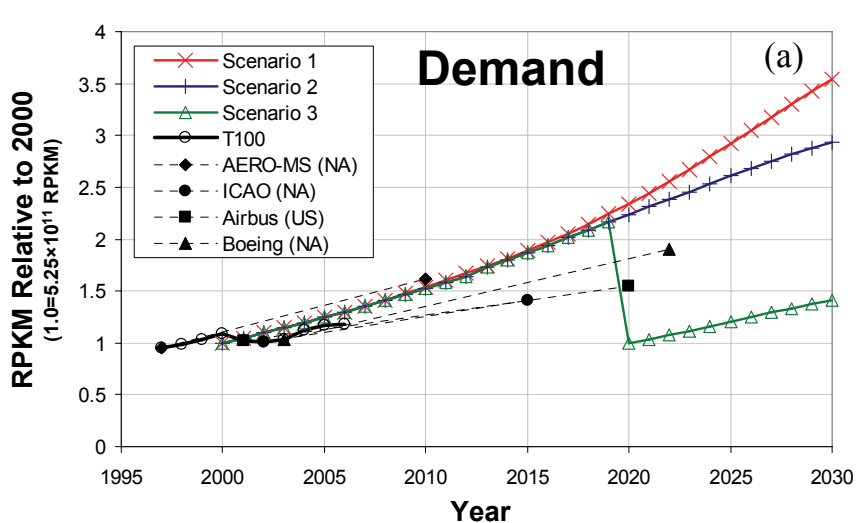
EDMS NO_x result
~1,000,000 sec



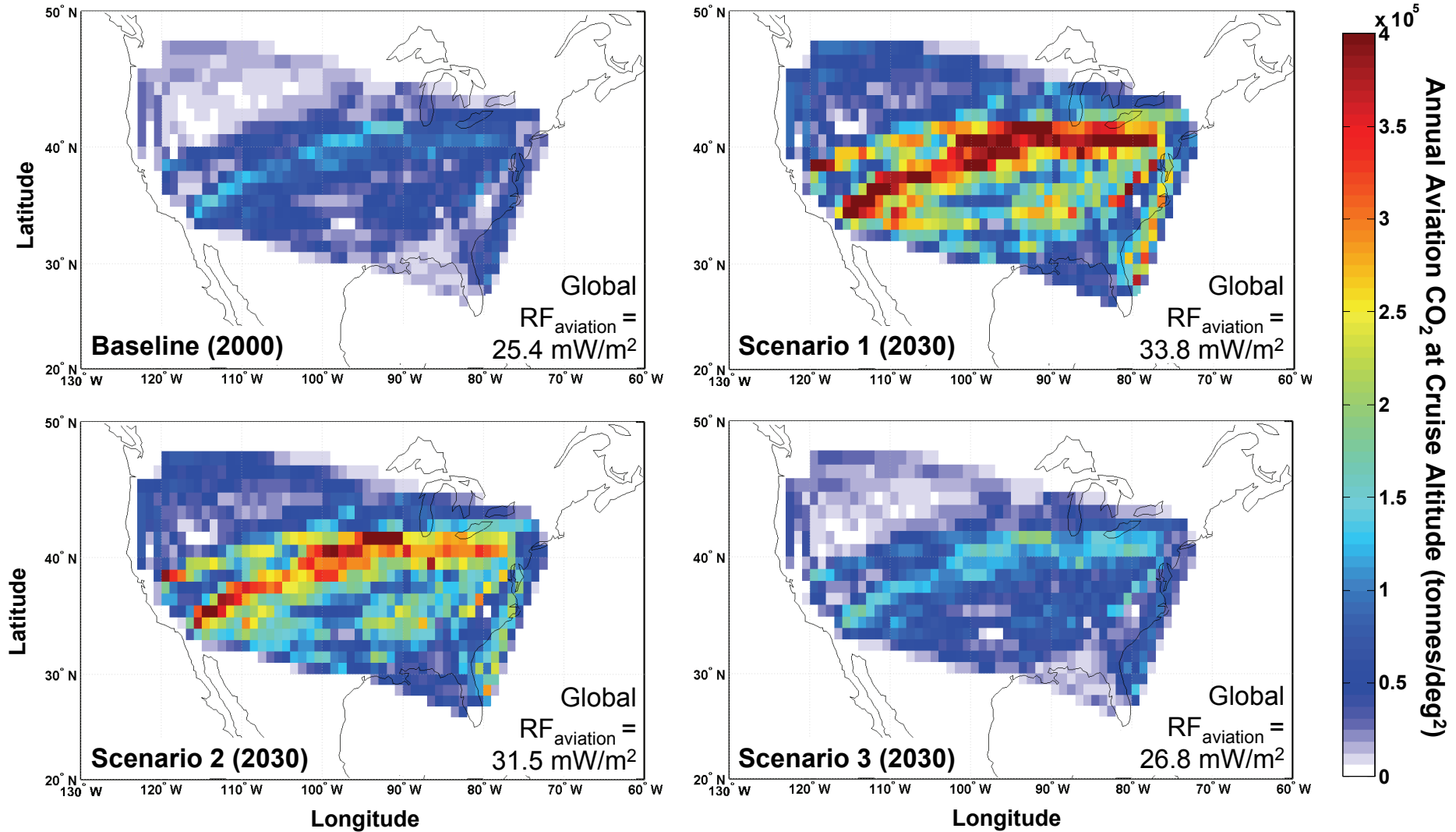
- Goals:** Quantify positive and negative economic effects of air transport activity on surrounding regions



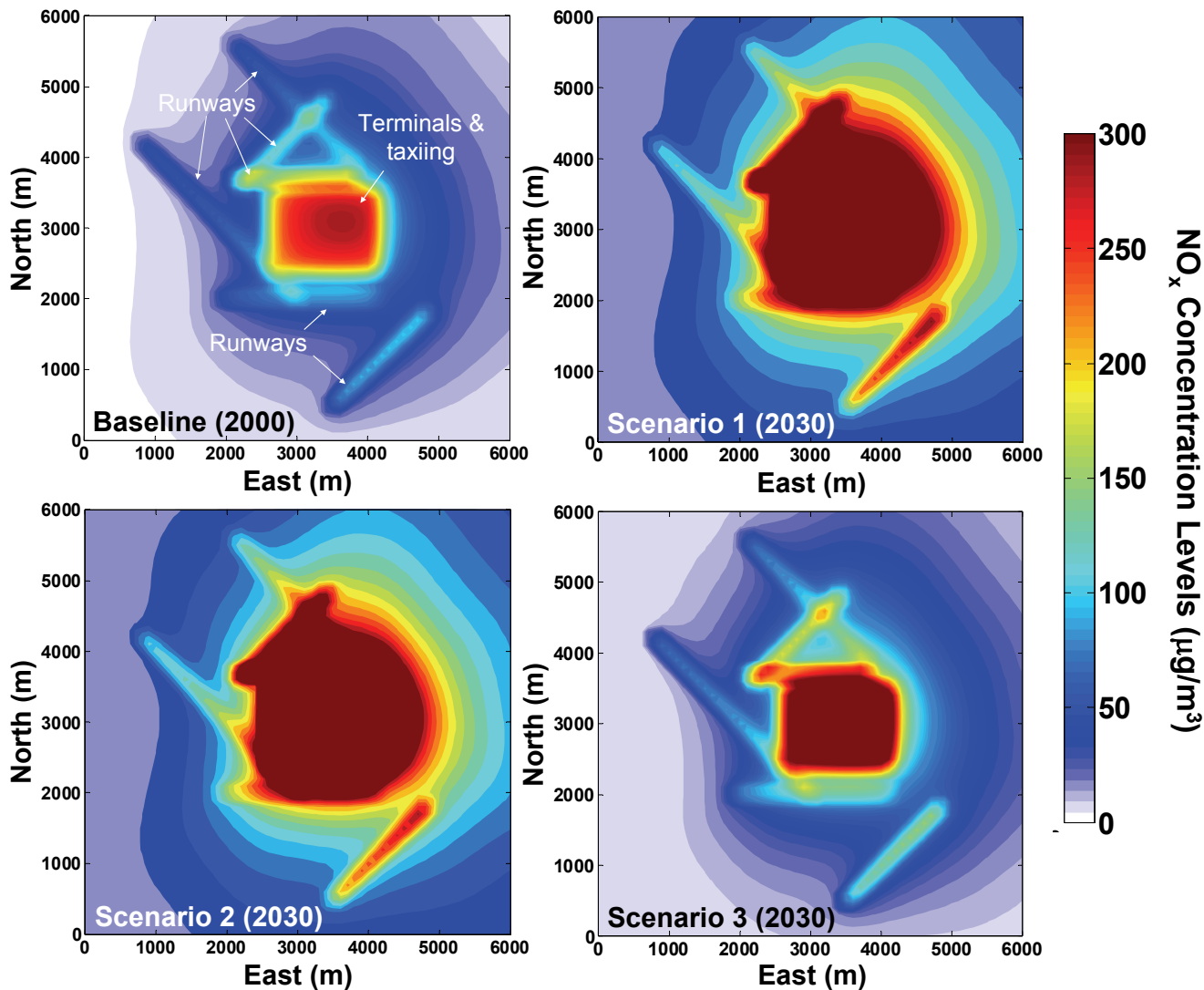
- Positive Regional Impacts
 - Direct (e.g. jobs at the airport)
 - Indirect (e.g. jobs at local hotels, business relocation)
 - Induced (e.g. jobs at suppliers of local hotels)
- Negative Regional Impacts
 - Local air pollution (NO_x , SO_x , $\text{PM}_{2.5}$) – health impacts
 - Noise around airports – lowers property values
 - Visual intrusion, landscape degradation
 - Climate impacts through contrails and emissions
- Literature review → ‘Conversion factors’ to convert pollutant concentration or marginal effect of emissions into health effects/economic costs.



- Importance of feedback of delay effects
 - 20% reduction in demand in 2030 with Scenario 2
 - 15% reduction in operations in 2030 with Sc. 2
 - Less than demand reduction: higher proportion of smaller aircraft
 - 50% reduction in average arrival delay in 2030 with Sc. 2
 - Highly non-linear behaviour of delay with operations, especially when close to capacity
- Policy analysis provides interesting insights
 - High per-km tax required to reduce demand to 2000 levels
 - 7.7 cents/km equates to \$300 extra New York-Los Angeles
 - Demand falls to 2000 levels but operations fall less
 - Short haul demand less sensitive to price increases (business pax)
 - Higher proportion of short-haul traffic after policy introduction



- Compared to Baseline Emissions...
 - Large increase in Scenario 1 en route emissions
 - Concentration in heavily-travelled trans-continental routes
 - Smaller increase in Scenario 2 en route emissions
 - From dampened demand and operations
 - Evidence of emissions increase in Scenario 3
 - Demand creeps back 10 years after introduction of policy
- Global radiative forcing perturbation analysis shows similar trends
 - Scenario 1 up 8.4 mW/m² by 2030, Scenario 2 up 6.1 mW/m², Scenario 3 up 1.4 mW/m² relative to baseline 25.4 mW/m² in 2000



- Rapidity of LAQ algorithm allows a large number of airports to be modelled – case study focus on ORD
 - NO_x concentrations reflect prevailing winds and current/predicted runway usage
 - Taxi and terminal area emissions dominate over runway emissions as delays increase
- Probability of violating current NO₂ regulations in Scenario 1 and 2
 - Policy measures may be required to avoid this
 - Emissions increase due to increased operations and delays, so capacity increases produce temporary improvement

- Modelling world passenger and freight demand
 - Focus on developing markets, e.g. S and E Asia
 - Business vs. leisure consideration
 - Passenger mode choice
- Airline response model
 - Capture effects of airline schedule/routing/fleet modification behaviors with changing operating environments
- Modelling of future aircraft/engine technologies and their likely introduction to system
 - Incremental designs: higher efficiency
 - Novel configurations: open rotor engines, blended wings
 - Alternative fuels

- AIM developing policy assessment tool for aviation, environment and economic effects
- Breadth and depth of model presented
- Case study results demonstrate utility of approach
- Geographical expansion is important to model global effects
- Future enhancements planned

- Data Analysis?
 - Demand modelling
 - Passenger numbers, routing, income data
 - Airport Activity modelling
 - Airport capacities, delay statistics
 - Air Traffic modelling
 - Flight data, future developments in Air Traffic System
- Relevant Indian/South Asian Case Studies?
- Researcher exchange/Workshops?

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Primary funding for AIM is from:

EPSRC

Engineering and Physical Sciences
Research Council



**NATURAL
ENVIRONMENT
RESEARCH COUNCIL**

Their support is gratefully acknowledged