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Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation

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A B S T R A C T

With increasing demand for air transportation worldwide and decreasing marginal fuel efficiency improvements, the contribution of aviation to climate change relative to other sectors is projected to increase in the future. As a result, growing public and political pressures are likely to further target air transportation to reduce its greenhouse gas emissions. The key challenges faced by policy makers and air transportation industry stakeholders is to reduce aviation greenhouse gas emissions while sustaining mobility for passengers and time-sensitive cargo as well as meeting future demand for air transportation in developing and emerging countries. This paper examines five generic policies for reducing the emissions of commercial aviation; (1) technological efficiency improvements, (2) operational efficiency improvements, (3) use of alternative fuels, (4) demand shift and (5) carbon pricing (i.e. market-based incentives). In order to evaluate the impacts of these policies on total emissions, air transport mobility, airfares and airline profitability, a system dynamics modeling approach was used. The Global Aviation Industry Dynamics (GAID) model captures the systemic interactions and the delayed feedbacks in the air transportation system and allows scenarios testing through simulations. For this analysis, a set of 34 scenarios with various levels of aggressiveness along the five generic policies were simulated and tested. It was found that no single policy can maintain emissions levels steady while increasing projected demand for air transportation. Simulation results suggest that a combination of the proposed policies does produce results that are close to a "weak" sustainability definition of increasing supply to meet new demand needs while maintaining constant or increasing slightly emissions levels. A combination of policies that includes aggressive levels of technological and operations efficiency improvements, use of biofuels along with moderate levels of carbon pricing and short-haul demand shifts efforts achieves a 140% increase in capacity in 2024 over 2004 while only increasing emissions by 20% over 2004. In addition, airline profitability is moderately impacted (10% reduction) compared to other scenarios where profitability is reduced by over 50% which pose a threat to necessary investments and the implementation of mitigating measures to reduce CO2 emissions. This study has shown that an approach based on a portfolio of mitigating measures and policies spanning across technology and operational improvements, use of

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biofuels, demand shift and carbon pricing is required to transition the air transportation industry close to an operating point of environmental and mobility sustainability.

1. Introduction

1.1. Motivation and background

Historically, air transportation activity has exhibited significant growth (Fig. 1). North America and Europe have grown at an average annual rate of 5.7% and 5.0% respectively over the last 20 years. Asia-Pacific has exhibited significant growth (i.e. 8.8%) and is now reaching traffic levels comparable to Europe. Impressive growth has also been observed in the Middle East with 13% annual growth between 2000 and 2007. Schafer and Victor (2000) affirm expectations that the impetus for these growth rates for aviation will be maintained using a time-budget model to project growth rates across transportation sectors.

However, air transportation activity is also a contributor to greenhouse gas emissions (e.g. CO_2, NO_x) and future growth of this industry sector is likely to be accompanied with increasing emissions unless significant efficiency improvements and mitigating measures are implemented. The Intergovernmental Panel for Climate Change (IPCC) evaluated the effects of the transportation sector on climate change using scenarios to forecast the demand and emissions of the different modes (IPCC, 1999; Ribeiro et al., 2007). These forecasts were building on work from the United States Energy Information Administration (EIA, 2005), the International Energy Agency (IEA, 2004) and the World Business Council on Sustainable Development (WBCSD, 2004).

As shown in Fig. 2, CO_2 emissions from air transportation are expected to increase significantly in nominal terms. While the relative contribution of the aviation sector to the global anthropogenic carbon emissions is currently estimated at about 3%, the higher potential for improvements and emission reductions from other sectors are likely to contribute to an increase in the aviation's relative contribution. The 1999 IPCC report suggests that this contribution may rise to 5% and could reach up to 15% by 2050 (IPCC, 1999).

The GHG emissions generated by aviation are not limited to CO_2. The IPCC (1999) and Sausen et al. (2005) estimate the relative contribution of CO_2 to total green house gas (GHG) effects to be approximately 53%. Lee et al. (2009) present the most recent information on the relative contribution of other GHG gases from the aviation sector and estimate the total radiative forcing from aviation to be 3.5% of total anthropogenic forcing excluding the effect of clouds. The net effect of NO_x emissions that increase ozone (i.e. O_3) concentrations and decrease methane (i.e. CH_4) is estimated at 24%. The effect of contrails is estimated at 21% and the remaining combined effect of H_2O, SO_x and soot contributes to 2.1% of the total effects.[3] These annual impacts of emissions do not address the different life cycles of the gases. Marais et al. (2008) indicate that the long-term effect of carbon emissions, which also happen to have the longest atmospheric life exceeding 100 years, may dominate the effect of other greenhouse gases depending on the evaluation method used and the discount rate. Because of its high relative contribution to GHG effects, its long lasting impacts and the high uncertainty surrounding non-carbon radiative forcing, this paper will solely focus on the CO_2 emissions from aviation.

It is expected that the anticipated increase in the relative contribution of aviation to global CO_2 emissions will reinforce the public and political pressure and force the air transportation sector to reduce its greenhouse gas emissions. Given that air transportation is a vital underlying infrastructure and enabler of the global economy by facilitating flows of passengers and goods, there is the need to find means to transition air transportation to a sustainable industry. Sustainability is defined, in the broad sense, as the ability to maintain a certain process or state from three perspectives (1) environmental, (2) social and (3) economic. Based on this definition, a sustainable air transport system would have a negligible environmental footprint while satisfying the transportation needs of a globally connected society and providing adequate returns on investment to attract and retain investors, employees, and the supporting value chain. For the purpose of this research, we will define the *short-term* sustainability objective as *the ability to (1) maintain CO_2 emissions at or below 2004 levels while (2) meeting increased mobility needs -measured in Revenue Passenger Kilometers (RPKs)- above historical levels.*

1.2. Key levers to reduce CO_2 emissions from commercial aviation

In order to achieve the sustainability objective defined in Section 1.1, there is the need to reduce CO_2 emissions at a rate equal or greater than the rate of increase of traffic. Reduction of CO_2 emissions from aviation can be achieved through five key levers:

- *Technological efficiency improvements*: relate to vehicle (i.e. aircraft) fuel efficiency performance.
- *Operational efficiency improvements*: include effects of airline operations (e.g. aircraft weight reductions by removing unnecessary onboard equipment) and air traffic control operations (e.g. fuel optimized flight path, altitude, reduced ATC delays, etc.).

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[3] Note: The potentially significant effects of cirrus cloud seeding were entirely excluded from this analysis due to the uncertainty in this estimate.

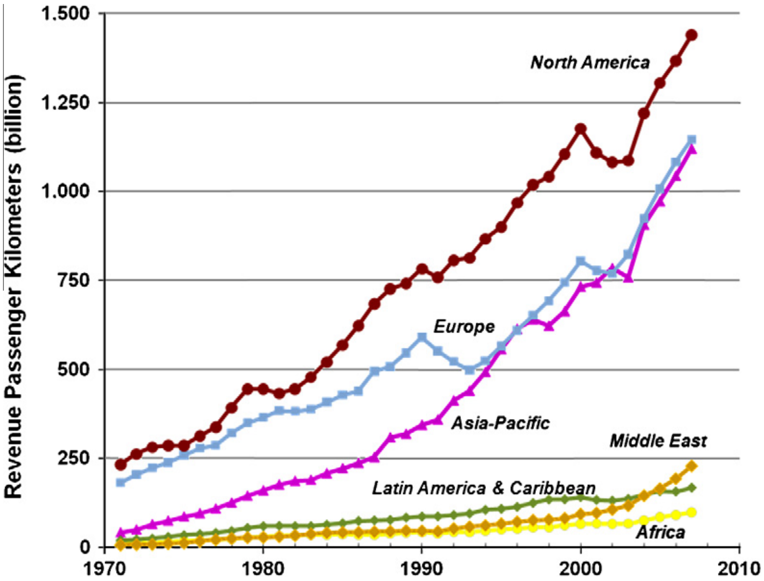

Fig. 1. Passenger traffic (Revenue Passenger Kilometers) worldwide from 1971 to 2007, (data sources: ICAO 2000, 2001–2006, IATA, 2008a).

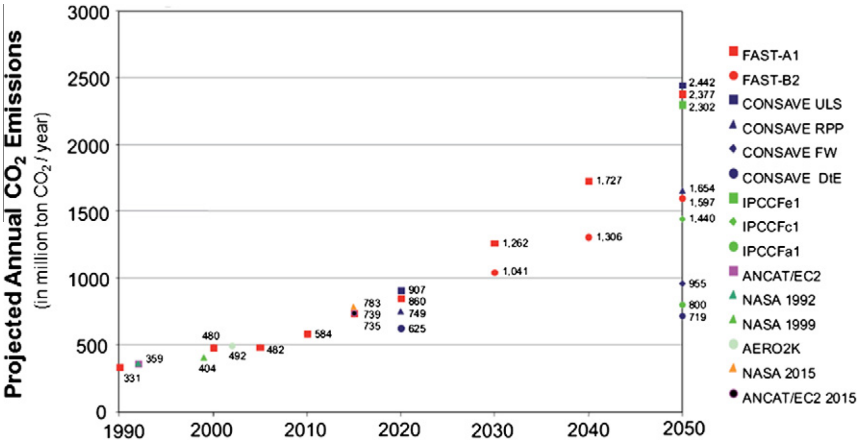

Fig. 2. Global CO_2 emissions forecasts for commercial aviation based on various studies (source: IPCC Ribeiro et al., 2007).

- *Use of alternative fuels*: capture the use of fuels that have a lower CO_2 emission content than traditional jet fuels.
- *Demand shift*: account for changes in travelers' mode choice behavior or reduction of demand due to non-travel alternatives (e.g. video-conferencing, virtual meetings, etc.).
- *Carbon pricing (i.e. market-based incentives): used* as a mechanism to increase the effective price of fuel and reduce demand through the price-demand elasticity relationship.

These key levers were used as a basis for the generation of scenarios used as inputs in a Global Aviation Industry Dynamics model to evaluate the potential reduction of CO_2 emissions from aviation for the 2004 to 2024 time period.

1.3. Approach and outline of the paper

In this paper, we approach the evaluation of the sustainability options available to aviation as Stanley et al. (2009) did for the options available to reduce the climate change impact of the Australian road transport sector. Unlike road transport, the global aviation industry is highly interdependent, i.e. it exhibits a tight coupling of the value chain (e.g. for the interconnection between operational strategies and financing cf. Scheraga 2004) and is prone to cyclical fluctuations in profitability (cf. for example Liehr et al. 2001) that ultimately influence fleet size and technological characteristics including fuel consumption efficiency.

This paper used a system dynamics modeling approach to capture the feedback dynamics governing the air transportation system and its impact on CO_2 emissions (cf. Section 2). This approach was motivated by the recognition that the behaviors of the stakeholders involved in the air transportation enterprise are dynamic over time. Their reaction to external changes (e.g. economic conditions and fuel prices) triggers changes in internal behaviors (e.g. aircraft utilization, fleet turnover, competitive conditions). This Global Aviation Industry Dynamics (GAID) model was then used to simulate and investigate the long-term impacts (i.e. 20-year) of different policies and strategies towards the goal of a sustainable air transportation system (cf. Section 3). Finally, the findings, discussion and conclusions from the model and their implications for policy makers are presented in Section 5.

2. Modeling the Global Aviation Industry Dynamics

2.1. Overview of the Global Aviation Industry Dynamics (GAID) model

The dynamics that describe the global air transportation system are governed by feedbacks and time dependencies, stakeholder interactions and decision processes, and non-linearity that make it hard for simple extrapolation models to capture and test future dynamics of the system. For the purpose of this study, a system dynamics model of the air transportation system was used to capture the effects of these interactions. Abbas and Bell (1994) make the case that system dynamics modeling can be a useful tool for understanding transportation system interactions as it captures supply and demand equilibrium, both short and long-term system behavior including lead times for fleet turnover, and can be used as an experimental tool for option analysis. In addition to these, the industry dynamics of tightly coupled value chains can be captured (Forrester, 1961), a characteristic that has led to a number of aviation industry applications (e.g. Liehr et al., 2001; Lyneis, 2000).

The Global Aviation Industry Dynamics (GAID) model extends the approach followed by Lyneis and Liehr et al. and is extensively described in Sgouridis (2007). A detailed summary is also provided in Appendix I. The general architecture of the model including key feedback dynamics, inputs and outputs is shown in Fig. 3. The GAID model captures the behaviors of the three primary stakeholders in the global aviation industry; passengers, airlines, and aircraft manufacturers.

The underlying demand for air transportation is defined in relation to economic activity (i.e. economic growth rate of gross world product), fares through the relationship of price-demand elasticity and is also influenced by exogenous demand shocks. The GAID model emulates the competitive dynamics in the airline and aircraft manufacturing industries as they influence fare pricing, aircraft orders, manufacturing rates and deliveries. In response to the underlying demand, airlines maintain a fleet of active aircraft that defines the upper limit in their operational capacity at any given time. Airline pricing

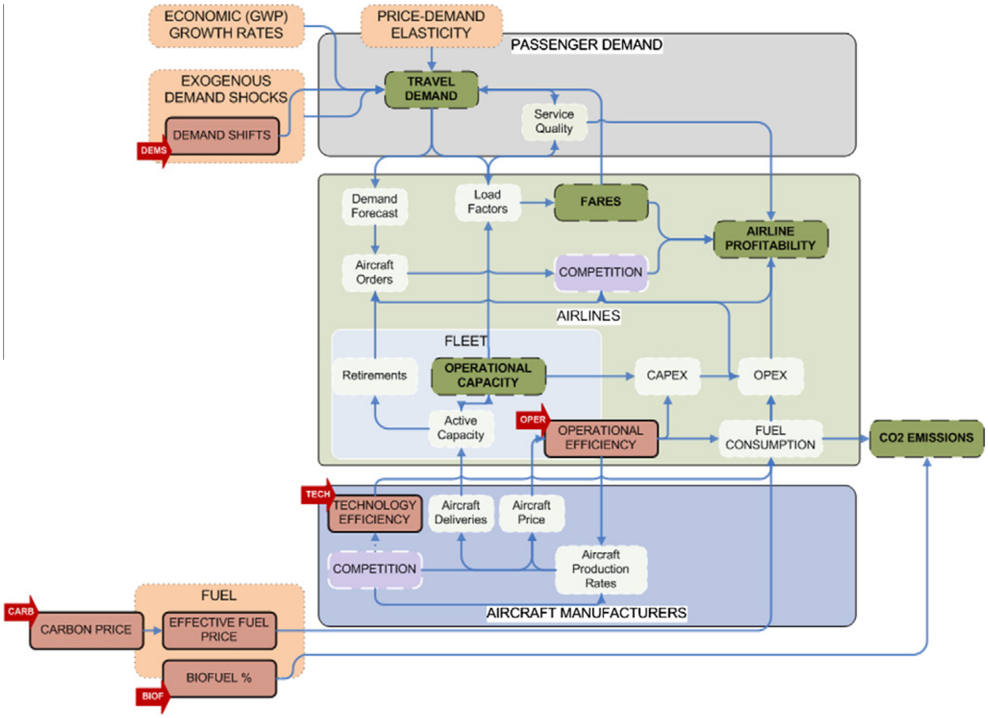

Fig. 3. General architecture of the Global Airline Industry Dynamics (GAID) model showing key dynamics, inputs and outputs.

(i.e. fares) depends on two main attributes: (1) the competitiveness of the industry as indicated by the number of effective competitors across markets and (2) the average load factors which based on yield management practices will allow higher fares to be set when load factors are high (i.e. when demand outstrips supply). Airlines manage supply by parking and retiring aircraft in the shorter term and by ordering aircraft based on their forecasts in the longer term. When the industry is profitable, new airlines are more likely to enter the market and the combination of incumbents and new entrants will tend to collectively over-order based on optimistic expectations, spurred by the need to invest their profits, and by discounting the effect of the orders that are already in backlog.

Manufacturers face their own competitive dynamics and try to capture market share as this enables both economies of scale and learning by doing but also creates a vendor lock-in effect for their customers. As aircraft orders peak during boom times manufacturers are slow to respond and ramp up production increasing lead times to delivery and creating a sense of scarcity that in turn induces phantom orders. The orders placed during the boom in demand are delivered even as demand growth rates slow down when the economic cycle reverses.

The general architecture of the model shown in Fig. 3 ignores some feedback dynamics that exist between CO_2 emissions and the other components of the model. Such dynamics include for example; *CO_2 emissions → Environment (Climate Change) → Public Perception → Travel Demand,* which is a balancing loop. Other examples include; *CO_2 emissions → Environment (Climate Change) → Public Perception → Government → Carbon Price* or *CO_2 emissions → Public Perception → Government → Emission Standards for Aircraft Manufacturers → Technology Efficiency*.

Since these feedback loops (external to the air transportation system) cannot realistically be modeled, these loops were shortcut and replaced by entry points into the system corresponding to the five key levers that are used to evaluate strategy and policy changes; (1) Technological efficiency improvements (TECH), (2) Operational efficiency improvements (OPER), (3) Use of alternative fuels (BIOF), (4) Demand shift (DEMS), and (5) Carbon pricing (CARB).

2.2. General assumptions

Several external inputs to the GAID model are used to calibrate the model based on historical time series data. These include (1) the global economic activity through the growth rate of the *gross world product*, (2) *exogenous demand shocks* that disproportionately affect air travel compared to their effect on global economy like terrorism events, pandemics and wars, (3) *fuel prices*, and (4) *price elasticity of demand*. In order to project the results of the GAID model into the future we needed to assume a scenario of the world status for the period 2004–2024. Our assumptions for the future can be summarized as follows:

- Global economic growth continues historical patterns with no catastrophic crashes occurring in this period but there is a succession of higher and lower growth rates with the occasional boom and busts. Rather than using a linear forecast, created a realistic time series by replicating the historical time series of economic growth to extend into the future. This provided us with the necessary realism of historical economic behavior with a succession of real economic cycles. Inclusion of a realistic exogenous economic cycle is necessary as the model's dynamic behavior depends to a certain extent on the variability and "unpredictability" of the inputs. If the global economy was deterministically growing at a given pace year after year, the planning process of businesses would be very different than what is observed in practice.
- Similarly, the passenger and shipper behavior as characterized by demand elasticity is maintained at historical levels.
- Liquid fuel production reaches a plateau but does not decline rapidly and remains available. Prices are more volatile than historical fluctuations and they follow a rising trend on average price of about 3.5% a year but with significant deviations from the trend (volatility) from year to year. This assumption follows the latest forecasts for liquid fuels IEA (2008).
- The regulatory environment that characterizes the airline market competitive dynamics is stable and liberalized (i.e. there are no fundamental changes in the regulations that limit how airlines price their fares or enter and exit domestic and international markets). As a result of this, organizationally, airlines and aircraft manufacturers are expected to maintain consistent behaviors to historical patterns.
- There are no major catastrophic events from climate change, large-scale conflicts, pandemics, etc.

The reason for choosing a rather optimistic scenario that suggests growth of demand for air transportation while allowing the exploration of adaptation to efficiency improvements and emission reduction is to avoid trivial results. In the event of drastic demand destruction for air travel due to socioeconomic upheavals, the volume of emissions from aviation will be reduced by default. It is far more interesting to consider policies of reducing emissions while the demand for this service is still thriving. In addition, the objective of a establishing a sustainable air transportation system is not to cap or limit growth of demand across the industry, but rather allow this growth (i.e. in both developed but also developing and emerging countries) while minimizing the environmental impacts of aviation through the set of measures.

3. Scenarios and assumptions for policy analyses

The five key levers to reduce aviation's CO_2 emissions presented in Section 1 were used as the basis for the generation of scenarios used as inputs in the GAID model to evaluate the potential reduction of CO_2 emissions from aviation. The time period of simulation ranged from 2004 to 2024. The scenarios are based on three supply-side policies (i.e. technological efficiency improvements TECH, operational efficiency improvements OPER and use of alternative fuels BIOF) and two demand-side (i.e. demand shift DEMS and carbon pricing CARB).

For each scenario, three levels of implementation aggressiveness are defined (1) baseline, (2) moderate and (3) ambitious. (e.g. TECH1 indicates the baseline scenario of technology improvements and TECH2 and TECH3 indicate the moderate and ambitious). Table 1 summarizes the assumptions that were used for each of the alternative (i.e. technological efficiency, operational efficiency, etc.) for the baseline (1), moderate (2) and ambitious (3).

3.1. Assumptions for single policy scenarios

3.1.1. Technological efficiency improvements

The technological efficiency improvement scenarios capture a set of measures related to vehicle (i.e. aircraft) performance including; (1) improved engine design such as 3D compressor blades, (2) improved aerodynamics using laminar flow wing profiles, non-planar wings, active wings, (3) reduced aircraft empty weight through the use of lightweight material such as composites, reconfigure airplane interior, etc.

Improvements in fleet efficiency from aircraft technology generally materialize at a slower rate due to significant time constants to develop and to diffuse new vehicles into the fleet. The long life expectancy of aircraft, which are capital-intensive assets, and, to a lesser degree, lock-in dynamics result in slow technology adoption rate. Historically, engine and aerodynamic efficiency improvements reached 1.5% and 0.4% per year respectively (Lee et al. 2001).

For the purpose for this research, it was assumed that technology efficiency improvements would reach 1% annually for the baseline scenario (TECH1). The TECH2 scenario (i.e. moderate scenario) assumes a 2.5% per year (i.e. equivalent to having new aircraft enter the fleet that are 35% more efficient than current (2008) average by year 2024). The TECH3 scenario is frontloaded in an effort to reduce the effect of the 10–15 year technology diffusion time due to fleet turnover rates (i.e. improvement rates of 3.5% per year between 2008 and 2015 and 0.6% per year thereafter).

There are no additional costs simulated for the improved efficiency as they are hard to define with any accuracy. Therefore, the increase in airline profitability that may result from improved efficiency is an upper boundary indicator of the industry's willingness to pay for the improvement.

3.1.2. Operational efficiency improvements

Operational efficiency improvements are achieved by changing the airline and air traffic control operations of the aircraft. This is achieved by (1) *aircraft weight reduction* such as reducing fuel ferrying practices, limiting the number and weight of baggage, etc. (2) *optimize flight operations for fuel consumption* which includes measures such as reduce cruise speed, optimize climb/descent paths, operate at optimum cruise level, use continuous decent approach, etc. and (3) *optimize ground operations* such as single engine taxi, optimize ground paths, minimize queuing, use tow-tugs instead of engine power for taxing, etc.

Table 1
Summary of policies and simulation assumptions.

Policy	Characteristic effect	Scenario	Quantified effect
Technological efficiency improvements	Fuel consumption per ton-km improvement per year in newly delivered aircraft due to technological innovation. In TECH3 the innovation effort is front-loaded. TECH2 and TECH3 lead to the same overall improvement at the end of the studied period	TECH1	1% Eff. imp. per annum (p.a.)
		TECH2	2.5% p.a.
		TECH3	3.5% p.a. (2008–2015) & 0.6% p.a. to 2024
Operational efficiency improvements	Additional improvement in fuel consumption per ton-km over baseline due to operational innovation (e.g. continuous descent approaches, one-engine taxiing, air traffic control system, etc.) Baseline assumes zero improvement	OPER1	0%
		OPER2	6%
		OPER3	12%
Use of alternative fuels	Percentage of biofuels used as drop-in replacement of fossil-derived aviation fuels to reduce carbon emissions	BIOF1	0% p.a.
		BIOF2	1% p.a.
		BIOF3	2% p.a.
Demand shift	Reduction in short and medium haul travel (<1500 km) over the baseline for reasons other than pricing. The figure indicates the reduction in travel achieved at the end of the simulation period	DEMS1	0%
		DEMS2	30%
		DEMS3	60%
Carbon pricing	Assumed price for emitted carbon by aviation fuel in constant US\$/CO_2 metric ton	CARB1	\$0/metric ton
		CARB2	\$50/metric ton
		CARB3	\$200/metric ton

Table 2
Relative performance of scenario against the baseline for CO_2 emissions, Revenue Passenger Kilometers (RPKs), airline profitability and average fare.

Category of scenario	Scenario	Policies					Simulation results			
		Technological efficiency	Operational efficiency	Use of biofuels	Demand shift	Carbon pricing	CO_2 Emissions (%)	Revenue Passenger Kilometers (RPKs) (%)	Airline profitability (NPV) (%)	Average fare (%)
Baseline	BASELINE	1	1	1	1		0	0	0	0
Focus on single policy	TECH2	2	1	1	1	1	−4	0.4	3	−1
	TECH3	3	1	1	1	1	−7	1	6	−3
	OPER2	1	2	1	1	1	−4	2	−0.3	−2
	OPER3	1	3	1	1	1	−7	4	−1	−3
	BIOF2	1	1	2	1	1	−5	0	0	−0.01
	BIOF3	1	1	3	1	1	−10	0	0	−0.03
	DEMS2	1	1	1	2	1	−11	−12	−16	−2
	DEMS3	1	1	1	3	1	−22	−21	−51	−3
	CARB2	1	1	1	1	2	−3	−3	1	3
	CARB3	1	1	1	1	3	−8	−9	0.3	13
L18 orthogonal array	EXP2	1	2	2	2	2	−20	−12	−14	−1
	EXP3	1	3	3	3	3	−36	−23	−51	3
	EXP4	2	1	1	2	2	−15	−13	−13	0.2
	EXP5	2	2	2	3	3	−35	−23	−52	4
	EXP6	2	3	3	1	1	−19	3	2	−4
	EXP7	3	1	2	1	3	−20	−6	7	6
	EXP8	3	2	3	2	1	−27	−10	−11	−6
	EXP9	3	3	1	3	2	−32	−20	−46	−6
	EXP10	1	1	3	3	2	−29	−21	−51	−0.5
	EXP11	1	2	1	1	3	−11	−7	1	10
	EXP12	1	3	2	2	1	−22	−10	−15	−5
	EXP13	2	1	2	3	1	−27	−21	−49	−4
	EXP14	2	2	3	1	2	−17	−0.1	7	−0.4
	EXP15	2	3	1	2	3	−25	−15	−15	5
	EXP16	3	1	3	2	3	−28	−17	−14	7
	EXP17	3	2	1	3	1	−32	−19	−46	−7
	EXP18	3	3	2	1	2	−19	2	8	−3
Additional Scenarios	MODER	2	2	2	2	2	−22	−12	−12	−2
	EXTRM	3	3	3	3	3	−39	−22	−47	1
	ALLSUP	3	3	3	1	1	−21	5	7	−6
	ALLDEM	1	1	1	3	3	−25	−23	−59	9
	SUP3DEM2	3	3	3	2	2	−30	−10	−10	−5
	SUP2DEM3	2	2	2	3	3	−35	−23	−52	4
	BIOCARB2	1	1	2	1	2	−7	−2	4	3
	BIOCARB3	1	1	3	1	3	−17	−9	1	11

Legend	1	Baseline
	2	Moderate
	3	Ambitious
	MODER	All moderate levels
	EXTRM	All high performance levels
	ALLSUP	Complete focus on supply side measures
	ALLDEM	Complete focus on demand side measures
	SUP3DEM2	Aggressive supply and moderate demand side
	SUP2DEM3	Mod. supply and ambitious demand (same as EXP5)
	BIOCARB2	Mod, biofuels and carbon pricing
	BIOCARB3	Ambitiousbiofuels and carbon pricing

Based on estimates from the Intergovernmental Panel on Climate Change (IPCC, 1999), system-wide scale operational efficiency improvements between 6% and 12% could be achieved. In our hypothetical future scenarios, we considered two cases using these IPCC estimates as an input range for the simulations. The moderate (OPER2) and ambitious (OPER3) operational efficiency improvement scenarios assumed a 6% and 12% respectively. In both cases it was assumed that the efficiency improvement is achieved fully by 2012 and remains stable thereafter.

3.1.3. Use of alternative fuels

There are several types and sources of fuels that could be used in the aviation industry as replacement of traditional jet fuels. Those are generally categorized into (1) traditional jet fuels from other fossil fuel sources, (2) synthetic fuel also called Fischer Tropsch (FT) fuels and (3) biofuels derived from biomass. For the purpose of simulating reduced CO_2 emissions from aviation, we will focus on the implementation on biofuels.[4] Biofuels comprise fuels from (1) *1st generation biofuels* produced from sugars, starches, oils or fats, that compete with food production and can have negative environmental impacts such as deforestation, (2) *2nd generation biofuels* made from sustainable sources of biomass such as forest residues, industry residues, municipal waste and sustainable grown biomass and (3) *3rd generation biofuels* made from sustainable, non-food biomass sources such as algae, switch grass, jatropha, babassu and halophytes.

Two scenarios for biofuels were evaluated[5]:

- BIOF2 assumes that biofuels are introduced and used in commercial aviation starting at 0.5% in 2009 and replacing 1% of traditional jet fuel per year (i.e. 1.5% in 2010, 3.5% in 2012, etc.)
- BIOF3 assumes that the same start date as the first scenario but with a more aggressive replacement fraction of 2% per year (i.e. 2.5% in 2010, 6.5% in 2012, etc.).

Both of these scenarios assumed that the 2nd generation of biofuels is used first (100% from 2011 to 2013 and then decreases to 45% in 2024) and that the 3rd generation enters service in 2014 to reach a 55% share in 2024. The CO_2 emissions from biofuels were assumed to be 70% and 20% for the 2nd and 3rd generations respectively compared to the emissions of traditional jet fuel. The price of biofuels was assumed to be equal to the price of fossil-derived jet fuel as they can be considered perfect substitute goods. This assumption makes the biofuels scenarios, when considered individually, trivial as the carbon reductions that they will be achieved can be calculated directly without the need for simulation by deducting from the baseline the proportion of non-fossil-carbon content of the biofuels. For this reason the biofuel scenarios were also combined with the carbon pricing scenarios as a carbon price creates an incentive to increase the use of biofuels, which are penalized only for their fossil-carbon content, and using biofuels is expected to reduce the effect of carbon taxes.

3.1.4. Demand shift

To capture the potential of a demand shift initiated by the users of the transportation system in response to climate change two scenarios were generated. The moderate scenario (DEMS2) and the ambitious (DEMS3) assumed a 30% and 60% demand shift from short-haul aviation or trips of less than 1500 km respectively.

It was assumed that the shift is accrued linearly and reaches the target value by the end of the simulated period 2024. Since short-haul trips are easier to substitute, this scenario focuses on this market segment and assumes that longer haul trips are not affected. This shift is assumed to be independent of pricing, as the GAID model already captures the elasticity of demand to price. This scenario is instead used to capture the dynamic of voluntary travel cutbacks or external restrictions applied onto the air transportation system.

Substitution modes and modified behaviors can include teleconferencing for business travelers, choosing vacation locations closer for leisure travelers. In order to provide substitution transportation modes, governments may provide incentives to build and use rail for short-haul trips or car-pool, buses, etc. Since this study only focuses on the emissions from the aviation sector, induced emissions from the substitution of modes (i.e. non-aviation modes) was not considered.

3.1.5. Carbon pricing (i.e. Market-based incentives)

Fuel consumption and CO_2 emissions can also be impacted through carbon pricing mechanisms such as cap and trade system or direct taxation. The cost of fuel is driven primarily by a demand–supply relationship where as worldwide fossil fuel consumption increases, price increases and conversely. In a carbon pricing scheme, a carbon price is set based on GHG emissions and fuel consumption. As the price of carbon increases, it increases the effective fuel price, which in turns reduces consumption through demand-price relationship.

To evaluate the effect of a carbon price on the effective price of fuel and ultimately on CO_2 emissions, two scenarios were tested; CARB2 assumed a real price of a metric ton of CO_2 to be US$ 50 (in 2005 constant dollars) and CARB3 assumed US$200 per metric ton of CO_2. This is approximately equivalent to an increase of the effective price of fossil-derived kerosene in the range of $0.5 to $2 per gallon of fuel.

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[4] While the use of biofuels can provide improvements in terms of reduction in CO_2 emissions, the use of synthetic fuel (e.g. coal to liquid (CTL), natural gas to liquid (GTL)) and traditional fuels from other sources (e.g. from tar sands, oil shale) can generate higher CO_2 emissions than current jet fuel. The use of these synthetic and traditional fuels from other sources can be motivated by energy independence arguments but are not necessarily beneficial from an environmental perspective.

[5] According to the International Air Transport Association (IATA), the 1st generation of biofuels is expected to generate 60% to 80% of the CO_2 emissions emitted by traditional jet fuel (IATA, 2008b). For the 2nd generation, the emission of CO_2 emissions would be less than 60% of traditional jet fuel and the 3rd generation would emit between 0% and 40%. While these biofuels for aviation are still in the phase of development and testing, the Commercial Aviation Alternative Fuels Initiative (CAAFI) estimates that the 2nd generation of biofuels could be certified and begin to be used on a commercial basis by 2010 and the 3rd generation by 2013.

3.2. Combinations of policies to generate multi-policy scenarios

The policies described in Section 3.1 investigated individual areas of improvement (e.g. technology efficiency improvement, operational efficiency improvement, use of alternative fuels, demand shift and carbon pricing). As none of the policies are mutually exclusive, they can be considered in a three level, five-factor design of experiments. We use a modified L18 orthogonal array to generate the experiment settings marked with the prefix EXP in Table 2.

In order to evaluate the Pareto frontier of the system performance (i.e. in terms of system output such as CO_2 emissions, passenger traffic, fares, airline profits) a set of 10 additional combinations of policies were evaluated. These scenarios were determined based on the following criteria:

- Evaluation of the moderate and ambitious achievements along each measure. The moderate scenario (MODER) assumes moderate improvements for each policy (i.e. TECH2 + OPER2 + BIOF2 + DEMS2 + CARB2). Similarly, the extreme scenario (EXTRM) assumes ambitious improvements.
- Emphasis on single dimension improvements. These five combinations focus of a push along one dimension of improvement. The ALLSUP scenario puts the emphasis on improvements from the supply side (i.e. maximum improvements from technical and operational efficiency as well as biofuels). The ALLDEM scenario uses a similar approach but on the demand side with aggressive demand shift as well as carbon pricing. The SUP3DEM2 and SUP2DEM3 scenarios were used to evaluate intermediate improvement scenarios that are probably more likely to happen than the single dimension ALLSUP and ALLDEM. Under the rationale that carbon pricing incentivizes the use of biofuels, two additional scenarios that combine this potential dynamic were tested (i.e. BIOCARB2, BIOCARD3).

4. Simulation results and discussion

4.1. Simulation results

By using the scenarios presented in Table 1 source not found, as inputs to the GAID model, a set of results for each scenario was obtained. These results track the impact of the changes associated with each scenario on key performance metrics; passenger traffic (i.e. measured in Revenue Passenger Kilometers), total CO_2 emissions, airline profits and average fares. Results are summarized in Table 2 by comparing the total impact of each scenario against the baseline performance.

Notes: All monetary values based on US constant dollars.
CO_2 emissions: Cumulative over time (Reduction considered positive).
Airline Capacity: Cumulative over time (Reduction considered negative).
Airline Profitability: Net Present Value (NPV) using a discount rate of 5% (Reduction considered negative).
Fare: Average fare across all years undiscounted (Reduction considered positive).

Fig. 4 shows changes in CO_2 emissions versus passenger traffic (i.e. measured in Revenue Passenger Kilometers) between 2004 and 2024 for each of the simulated scenario.Fig. 4 also shows the Pareto fronts within which the air transportation system is most likely going to operate. From this figure, four scenarios from the Pareto fronts (i.e. BASELINE, ALLDEM, EXTRM, ALLSUP) were identified and used for more detailed time series analysis as presented in Fig. 5.

4.2. Discussion of simulation results for single policy scenarios

4.2.1. Fleet technology efficiency improvements

As shown in Fig. 4 and Table 2, the scenarios relying on technology efficiency improvements (i.e. TECH2 and TECH3), while helping to reduce emissions, creates an induced demand effect. Due to the combined effect of more aggressive efficiency improvements in the first years and the fleet turnover dynamics, the TECH3 scenario achieves a greater overall emission reduction across the simulated time period (i.e. 7.3% reduction for TECH3 compared to 4% for TECH2). This suggests that strategies that focus on short-term improvements of the fleet are more effective from a CO_2 emissions perspective. In addition, the reduction of cost associated to the improved fuel efficiency also appears to have an effect on airline profitability compared to the baseline scenario (3.1% and 5.8% improvement in profitability respectively for TECH2 and TECH3).

4.2.2. Operational efficiency improvements

All else being equal, the system-wide CO_2 emissions reduction stemming from implementing solely the operational efficiency improvements are shown to be approximately half of what the rate of the improvement would be (i.e. 7.1% reductions in emissions for a 12% improvement in efficiency for OPER3). Similarly to the case of technology efficiency improvement, the reason for this lower effective CO_2 emissions reduction is induced demand generated by the reduction of operating cost and airfares. Passengers are the primary beneficiaries of improved efficiency and reduced fuel consumption. The competitive behavior of airlines leads them to translate most of the savings in operating costs achieved from the gains in efficiency to lower costs for the passengers. Through price-demand elasticity, lower fares then translate into induced demand and traffic.

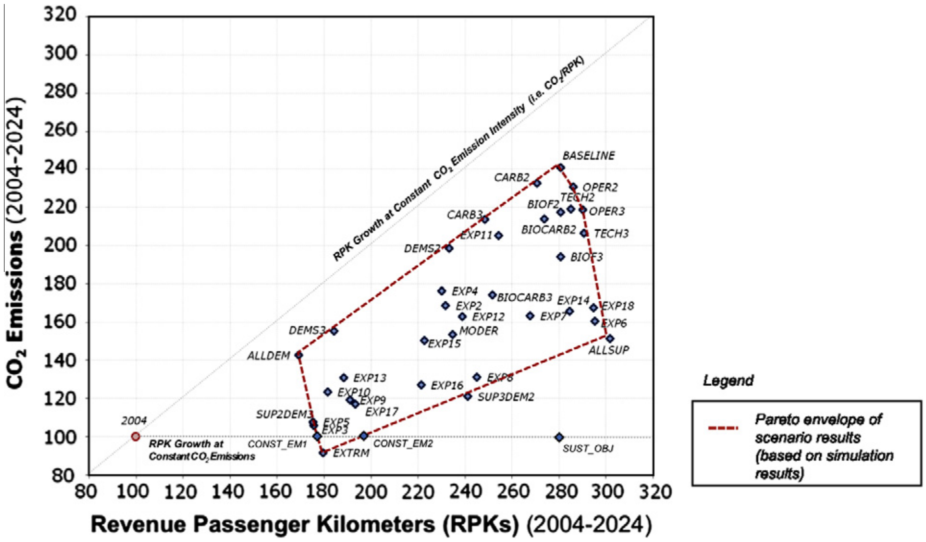

Fig. 4. Change in CO_2 emissions and Revenue Passenger Kilometers (RPKs) for all scenarios between 2004 and 2024.

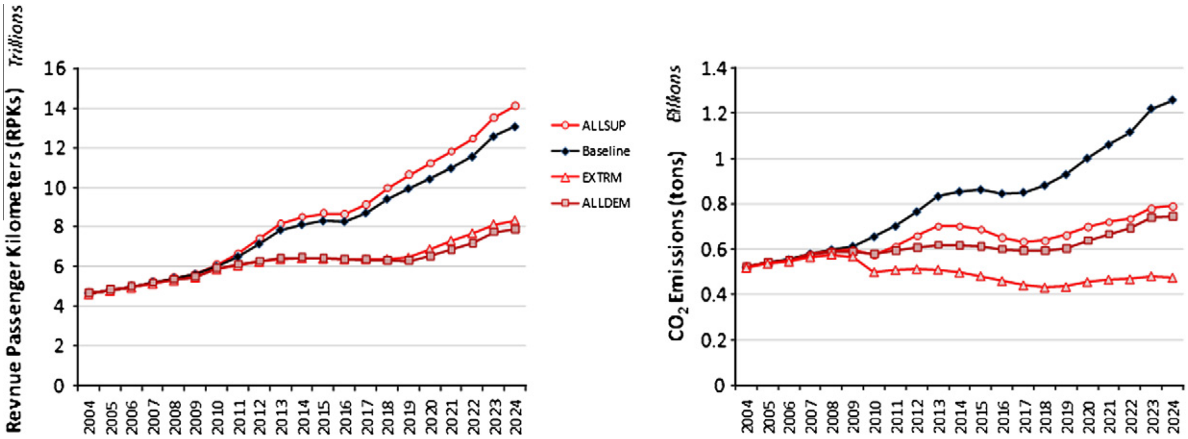

Fig. 5. Projected evolution of Revenue Passenger Kilometers and CO_2 emissions from 2004 to 2024 from the simulation of the GAID model.

4.2.3. Use of alternative fuels (i.e. biofuels)

Based on the simulation results, the relative impact of the use of biofuels result in a reduction of emissions by 5.5% for BIOF2 and by 9.5% for BIOF3. Combining the introduction of biofuels with a carbon pricing scheme (i.e. scenarios BIOCARB2 and 3) result in a reduction of CO_2 emissions by 6.6% and 17% respectively. While these results provide significant emissions reductions, limited synergies between the use of biofuels and carbon pricing were identified. Instead, the use of biofuels provides a respite from carbon prices and allows airline profitability to fare better than the baseline or the carbon pricing scenarios alone.

4.2.4. Demand shift

In the case of the demand shift scenarios DEMS2 and DEMS3, the reduction in emissions would be significant (11% and 22% respectively) and slightly lower than the reduction in capacity as airlines do not park or retire their aircraft to match the drop but rather operate at lower load factors. It should be noted that with this model, we only monitor the emissions from aviation. We did not consider whether the simulated non-price induced demand reduction is a result of demand destruction or of true modal shift so in the case of modal shift, the emissions of the substitute mode are not considered.

Airlines should be careful in managing such an eventuality as, in both cases, airline profitability potential suffers substantially during the peak of the cycle as the surplus capacity left in the system forces the airlines to compete on pricing but the losses are also somewhat limited during the trough as this lack of profitability curbs significant aircraft orders. Another observation from both demand shift scenarios is that when a number of users decide not to fly for reasons other than price, airline competition will still force the price lower and lure people with lower fares that would not fly if fares were higher. In other words, the reduction in emissions is not proportional to the numbers of original passengers that decided not to fly.

4.2.5. Carbon pricing (i.e. market-based mechanism)

Expectedly, the higher the carbon price, the lower the demand for air travel as airlines are eventually forced to pass on the extra costs to passengers. Interestingly, for the lower price scenario (i.e. $US 50 per ton), which is approximately the current level of carbon prices in the EU ETS, the impact on both demand and emissions is minimal (less than 3% of emissions reduction for CARB2). Based on the GAID model, it is only the higher level of pricing that starts to force a significant reduction (8.2% for CARB3). Notably, airline profitability does suffer in the beginning of the measure's implementation but after five years rebounds and stays close to the baseline as airlines shed capacity and consolidate thus being able to charge higher fares. These results from the simulations are consistent with the observations in 2008 of the reaction of airlines to the doubling of fuel prices from $2 to $4 per gallon within one year. As airlines tried to grapple with fuel price increases they initially absorbed the costs leading to bankruptcies of almost twenty smaller airlines while the larger players announced reductions in their capacity and mergers.

4.3. Discussion of simulation results from scenario of combination of policies

None of the policy when simulated individually managed to meet the sustainability criteria (i.e. ability to support historical demand growth rates while stabilizing emissions close to 2005 levels). The following section explores the results of the scenarios (i.e. combinations of policies).

As shown in Fig. 4, according to the baseline scenario passenger traffic would increase by 180% in 2024 against a growth of CO_2 emissions of 140%. For this scenario, the lower growth of emissions than passenger traffic is due to the baseline technology improvement of 1% per year. While other scenarios (i.e. combinations of CO_2 emission reduction policies) result in lower emissions -than the baseline case- the associated changes in passenger traffic vary widely. The ALLDEM scenario, including strong shift of demand to other nodes and high carbon price result in a limited 70% growth in traffic while the ALLSUP scenario focuses on technology and operational improvements with minimum impact on demand would result in a 200% growth of traffic. It should be noted that the net growth of CO_2 emissions in both cases is comparable (i.e. approximately 40 – 50%). Based on the simulation results, the case "EXTRM" which combines the most ambitious for each of the five key levers achieves a reduction of CO_2 emissions of 9% while increasing passenger traffic by 80%.

From Fig. 4, it is clear that the tighter sustainability objective (noted as SUST_OBJ in Fig. 4) is outside the Pareto envelope. As a result this objective does not seem to be achievable through the set of proposed measures and assumptions and would require more aggressive improvements in CO_2 emission reductions. There are however, combinations of policies that are close to this objective;

First, if the constant traffic growth rate criterion is relaxed (i.e. allowing lower growth rates of traffic than historical rates), a set of scenarios that meet the constant emission traffic growth criterion (i.e. maintain CO_2 emissions constant while increasing passenger traffic) can be identified from Fig. 4. Any scenario between the CONST_EM1 and CONST_EM2 points achieves this objective.

Second, scenarios on the Pareto front between the CONST_EM2 and ALLSUP represent tradeoffs between traffic and CO_2 emissions growth. The combinations SUP3DEM2, EXP16 and EXP8 manage a 120–140% growth of passenger traffic while only increasing emissions by approximately 20–30% and keeping airline profitability to less than 15% less than baseline. Overall, a strong push on the supply side (technology, operations, and biofuels) combined with a moderate support from demand side measures can provide results reasonably close to the sustainability objective.

5. Conclusions

With increasing demand for air transportation worldwide and decreasing marginal fuel efficiency improvements, the contribution of aviation to climate change relative to other sectors is projected to increase in the future. This is presented by Anderson et al. (2007) in the European Union context where by 2050 aviation contribution to total EU emissions limits could range from 10% to over 50% depending on aviation's rates of growth and efficiency improvement (assuming a 450 ppmv carbon budget goal). As a result, increasing public and political pressure targets air transportation to reduce its greenhouse gas emissions.

This paper examined five generic policies for reducing the emissions of commercial aviation; (1) technological efficiency improvements, (2) operational efficiency improvements, (3) use of alternative fuels (i.e. biofuels), on the supply side and (4) demand shift and (5) carbon pricing (i.e. market-based incentives) on the demand side. In order to understand and model the systemic interactions and the delayed feedbacks in the air transportation system, a system dynamic modeling approach was used. By simulating the air transportation dynamically, we found that no single policy implemented on its own would be able to meet the sustainability criterion of increasing passenger traffic at historical rates while maintaining emissions at constant levels.

According to the Global Airline Industry Dynamics (GAID) model, it was found that efficiency improvement policies would not generate sufficient emissions reductions on their own even when the boundary of expectations is pushed. Partly this is a result of the induced demand created by the reduction of operating costs, and consequently average fares, which in turn stimulates demand. Specifically, a 2% annual improvement in the specific fuel consumption of new aircraft will only yield less than 4% reduction in cumulative emissions between 2004 and 2024 due to the slow fleet turnover and induced demand. Similarly, operational efficiency improvements of 12% effective in 2008 would only reduce emissions by 7% due to induced demand. It should be noted that while technology and operational efficiency improvements induce demand and therefore reduce the effectiveness of CO_2 emission reduction, these improvements are necessary to achieve the desired traffic growth – at or close to historical growth rates.

Based on the model, it was found that demand management schemes become effective only if aggressive measures are implemented. Carbon pricing schemes would need to maintain high price levels. For example, a price of $200/metric ton of CO_2 would be needed for a total reduction of 8% of emissions compared to the baseline scenario. Diversion of travel demand to other modes and/or demand destruction would need to reach 60% of short-haul travel by 2024 in order for airline emissions to be reduced by more than 20%.

Based on the GAID simulation, the combined use of carbon pricing and biofuels would provide a significant contribution to the overall goal of reducing CO_2 emissions by resulting in a reduction of 7–17% reduction of CO_2 emissions by 2024.

A combination of more moderate measures though, does produce results that are close to a ''weak'' sustainability definition of increasing supply to meet new demand needs while maintaining constant or increasing slightly emissions levels. A combination of policies that includes aggressive levels of technological and operations efficiency improvements, use of biofuels along with moderate levels of carbon pricing and short-haul demand shifts efforts achieves a 140% increase in capacity in 2024 over 2004 while only increasing emissions by 20% over 2004. In addition, airline profitability is moderately impacted (10% reduction) compared to other scenarios where profitability is reduced by over 50% which pose a threat to necessary investments and implementation of mitigating measures that would reduce CO_2 emissions.

This study has shown that an approach based on a portfolio of mitigating measures and policies spanning across technology and operational improvements, use of biofuels, demand shift and carbon pricing is required to transition the air transportation industry close to an operating point of environmental and mobility sustainability.

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Appendix I:. Detailed summary of the Global Aviation Industry Dynamics (GAID) Model

I.1. Structure and scope of the GAID Model

The GAID model extends System Dynamics structures used in the aviation system modeling as presented by Weil (1996), Lyneis (2000), and Liehr et al. (2001). The model represents the dynamic interactions between the primary aviation industry stakeholders shown in Fig. 6 including aircraft manufacturers, airlines, and passengers.

The GAID model is intended to emulate the key dynamics of the industry while also allowing for experimentation with alternatives that would cause structural changes to the system. As a consequence the interactions modeled include:

- The competitive dynamics of a duopolistic market for aircraft manufacturers that include aircraft pricing, and the effects of economies of scale, scope, and vendor lock-in.
- The market dynamics of the global airline industry; differing competitive dynamics affected by the relative barriers to entry and exit and the profitability of the industry where high level of profitability induces higher entry rate which in turn suppresses fare prices as competition intensifies. Similarly, orders, utilization, and retirement of aircraft are dependent on the competitive dynamics; in a more competitive industry, the desire to fill the available aircraft and increase load factors in the short term will override the propensity to reduce capacity in an effort to improve profitability.
- The demand for air transport is dependent on economic and population conditions on one hand and on the reaction to price levels as demonstrated by the price elasticity of the consumers of the transport service.
- External effects not captured by the dynamics described previously like fuel prices and events that disproportionately affect air travel (e.g. a terrorist attack, regional war, or a pandemic) compared to their impact on the economy as a whole.

The model contains a total of over 1000 variables and 400 equations. A detailed presentation of the key variables and the equations that guide their values are provided in Chapter 9 of Sgouridis (2007).

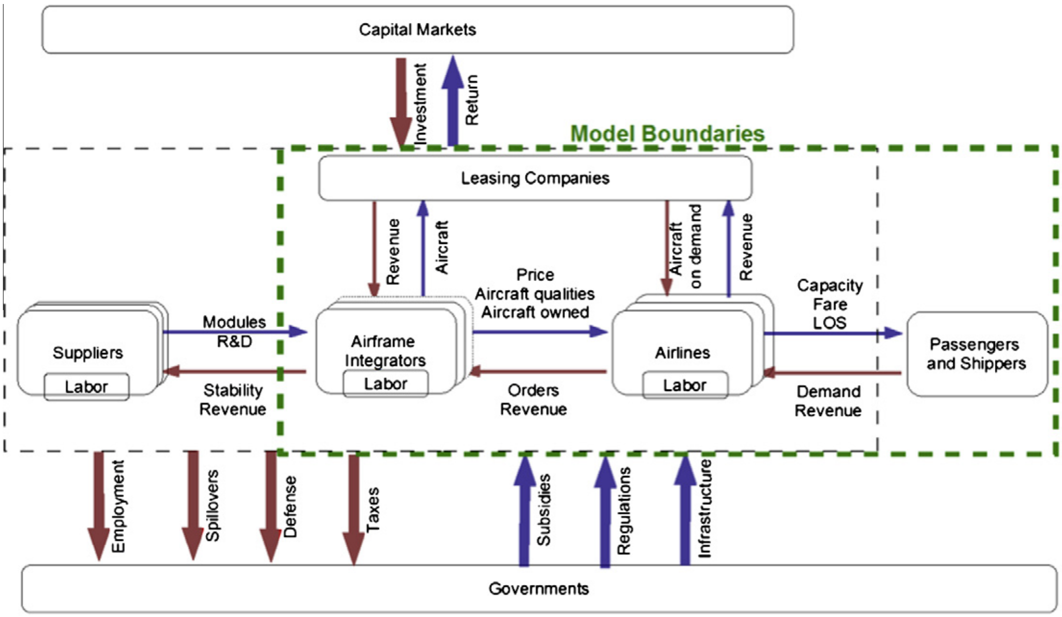

Fig. 6. Aviation industry stakeholders and GAID model boundaries.

I.2. Calibration and validation of the GAID model

The GAID model was intended for high-level policy analysis rather than detailed forecasting. The calibration process used a combination of historical data, derived parameter values based on econometric estimation, published estimates of specific parameters and, in the case of parameters where existing estimates were not available or were qualitative in nature, a reasonable estimate was used ac-companied by sensitivity analysis. In addition, the model's modular structure allowed for a sequential calibration/verification of each module by separating them and feeding historical data as inputs and monitoring the outputs compared to the historical expected values. Given the tight interactions between modules, this was an iterative convergence process.

The calibration used historical data starting in 1984 since by that time many of the current features of the industry were in the process of being established:

- Airline deregulation in the US market was well under way.
- Low-cost carriers (LCCs) were introduced and growing (Southwest, People Express, etc.).
- Yield management systems started to become widespread.
- Airbus had carved a niche for itself in the wide-body aircraft category and was about to introduce its narrow-body family.

For this reason the mid-eighties is a good starting point for the GAID model as it gives ample historical data for further calibration and does not have to account for major differences in industry structure. The key parameters used for calibration against historical data were:

- Airline total demand, operating capacity, and load factors.
- Airline revenues, costs, and profit margins.
- Airline orders and manufacturer backlog (aircraft delivery lead times are implicit in backlog).

Fig. 7 shows a sample of these parameters for airlines comparing model results against the historical data.

To confirm the visual indications of close similarity between the modeled and historical data, we also conducted a set of statistical tests for these key parameters summarized in Table 3. For all parameters the hypothesis that the model results are not significantly different statistically than the data distribution could not be rejected. We also notice from the fact that the *Uc* Theil statistic is greater than *Um* and *Us* that there is a phase shift between the model results and the historical data but does not give information as to the relative magnitude. By inspection, this phase shift is less than one year, which is a small time frame for the time-scales that we are considering. On the same topic, Sterman (2000, pp. 877) notes that the system type we are considering – a combination of supply chains and commodity markets – ''selectively amplify certain frequencies in the random shocks that constantly perturb them. Since no model can capture all the random variations in the environment, model dynamics can diverge from the data even if the model is perfectly specified''.

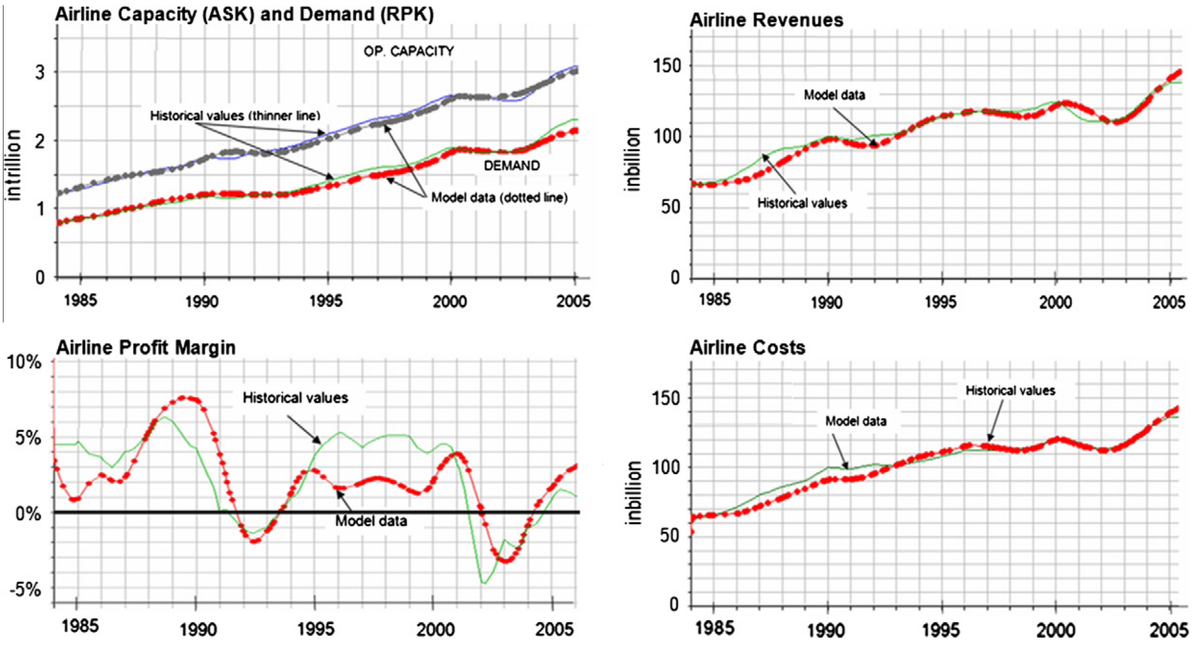

Fig. 7. Illustrations of comparative analysis of historic and modeled key outputs of the GAID model for calibration and validation.

Table 3
Statistical tests comparing the Historic Data distribution (d) with the model output data (m).

Variable	Mean, d	Mean, m	Sqrt. (MSE)	R sq.	Theil statistics			$P\ (T \leqslant t)$ two-tail	Statistically significant difference
					Um	Us	Uc		
Capacity (in trillion op. ASM)	2.03	2.03	0.077	0.981	0.001	0.153	0.845	0.986	No
Demand (in trillion RPM)	1.39	1.39	0.061	0.975	0.004	0.007	0.989	0.976	No
Load factors	0.68	0.68	0.020	0.43	0.019	0.002	0.979	0.718	No
Airline costs in (SB)	101	93.3	5	0.959	0.172	0.246	0.582	0.73	No
Airline revenues	103	101.1	5.2	0.949	0.152	0.185	0.663	0.735	No
Airline profit margins	0.026	0.027	0.018	0.663	0.003	0	0.997	0.916	No
Aircraft orders (in trillion ASM)	0.21	0.19	0.067	0.628	0.081	0.095	0.824	0.531	No
Aircraft backlog (in trillion ASM)	0.61	0.63	0.164	0.636	0.019	0.111	0.871	0.771	No

Finally, in order to create a meaningful background for experiments, we projected the key driving parameter variables (i.e. gross world product and population, fuel prices and external factors) to 2024 as explained in Section 2.2.

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