A General Equilibrium Analysis of Climate Policy for Aviation

by

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Abstract

Regulation of aviation's contribution to the global problem of climate change is increasingly likely in the near term, but the method agreed upon by most economists—a multi-sectoral market-based approach such as a cap and trade system—is opposed by industry stakeholders. An efficient economy-wide policy would determine the optimal level of sectoral emissions reductions, but industry groups have instead proposed independent aviation-sector goals for carbon mitigation and technology adoption. This thesis asks the question: how much should airlines reduce their emissions, and which technologies will be necessary to achieve those reductions.

In order to comprehend the problem of mitigation costs and outcomes within the context of the global economy, I introduce an aviation-resolved version of the MIT Emissions Prediction and Policy Analysis model; a computable general equilibrium model of the global economy. In EPPA-A, the social accounting matrix is re-balanced to include aviation, a non-unity income elasticity of demand is introduced, and substitution elasticity parameters are estimated. Additionally, I include an additional module to analyze the potential non-market impacts of government infrastructure on aviation emissions by explicitly modeling an advanced Air Traffic Control sector.

Several policy scenarios are applied to the model including: an idealized economy-wide cap and trade system in each developed nation or region, and an aviation-sector-only cap within an economy-wide cap, both with and without trading enabled between the aviation cap and the economy-wide cap. Each policy scenario is compared to a business-as-usual case, and relative welfare loss under each policy is calculated. The business-as-usual and economy-wide cap policies are also run with the advanced Air Traffic Control module enabled, and the efficacy is determined.

I find that in the context of total economic welfare, the method of aviation regulation is of little significance; the differences in results among the different policy scenarios are very small (on the order of 0.002% in the U.S.). However, the price of aviation and sector output are more responsive. When trading between an aviation-sector-only cap and the economy-wide cap is enabled, outcomes are practically identical. When trading is not allowed, the price of aviation increases 21.8%, and output falls 32.8% compared to the economy-wide policy-only case. I find that national welfare outcomes are sensitive to international trade, and border adjustments for aviation emissions are important. Finally, the efficacy of advanced Air Traffic Control infrastructure, and the economic welfare gained or lost, is sensitive to the parameter estimates which exhibit high uncertainty. I find that the low-efficacy parameters result in slightly lower fuel intensity, but are also net-welfare decreasing, while the high parameter estimates increase welfare, but result in an infeasible reduction in sectoral energy intensity.

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Chapter 1

Introduction

Civil aviation is an essential and growing component of the global economy, and is also one of the fastest growing sectoral sources of greenhouse gas emissions. But in the context of the global problem of climate change, aviation is also a relatively small contributor, responsible for about 3% of total anthropogenic warming in 1992 (Penner et al., 1999). It is important that any climate policy strike a balance between emissions reductions and the costs of abatement, but while economists generally agree that an economy-wide market-based instruments (such as a cap & trade scheme or carbon tax) are the most economically efficient methods of regulation, stakeholders such as the Air Transport Association oppose aviation's inclusion in market-wide regulation in favor of an industry-administered sectoral policy. The global sectoral "cap," would allow emissions growth until 2020, but then disallow any future growth in emissions from the aviation sector (ATA, 2010). In general, economic theory predicts that this type of sectoral cap would be a more costly policy proposal than an economy-wide policy would be. This study tests that assertion using a global Computable General Equilibrium (CGE) model while adding some additional considerations of non-market aspects of the aviation sector such as the potential for advanced air traffic control.

The role of aviation in the economy is relatively small in national accounting terms, but the services provided by aviation—rapid, long-distance, low-cost transport—enable and facilitate a large, and growing portion of domestic and international commerce (FAA, 2008). The measured income elasticity of demand for aviation consistently shows greater-than-unity estimates, predicting an increased share of aviation in future consumption. These estimates, driven by historical trends lead forecasters to anticipate sustained growth in demand for air travel (ICAO, 2008; FAA, 2011). But aviation emissions present one potential barrier to future growth. Commercial aircraft nearly universally rely on kerosene-type jet fuels, and regulation of their unavoidable byproducts of combustion—carbon dioxide and other pollutants—poses the risk of increased costs of production. Unlike land transport, however, the aviation sector has few alternative power sources which will be commercially available in the near term.

Because climate change is a global problem, the solutions must be international and pan-sectoral in scope. Therefore, the motivation of climate change policy analysis is the problem of finding policy prescriptions which mitigate greenhouse gas emission while reducing social costs of that policy, while seeking to understand the dominant drivers of policy cost and innovate upon policy options. Where the aviation sector is technologically constrained and likely faces high mitigation costs relative to other economic sectors, aviation emissions are a relatively minor source of anthropogenic warming. This analysis seeks to determine how and to what extent the aviation sector should play a role in GHG mitigation efforts.

In order to assess the impacts of climate policy on the aviation sector in a globally-comprehensive, and social-welfare-oriented context, I adapt the MIT Emissions Prediction and Policy Analysis (EPPA) model for analysis of the global aviation sector (Paltsev et al., 2005). EPPA provides a consistent framework for tracking the effects of climate policies on different commodity prices, and on intermediate and final demand for the products of economic sectors. EPPA for Aviation (EPPA-A) specifically models the aviation sector in each region, and endogenously calculates prices of and demand for aviation based on the requirements of a given climate policy. An additional module allows for a government-supplied advanced Air Traffic Control (ATC) infrastructure and considers both the social cost and benefits of such non-market allocations.

Policies considered in this thesis are designed to represent the likely outcomes of proposals by relevant stakeholders, and produce results which bear on the costs and benefits, both to the aviation sector, and to society as a whole. An idealized cap & trade policy for the industrialized world represents the recommendations of economic theory, while policies including sectoral caps for aviation represent those favored by the Air Transport Association (ATA) in the U.S. and internationally by the International Air Transport Association (IATA).

In Chapter 2, I present in greater detail the relevant economic and technological relationships between aviation and climate change, including the technological advancements which are commonly anticipated to curb emissions growth, and a background to the theory and application of policy instruments to the problem of climate externalities. In Chapter 3, I introduce a methodology for general equilibrium analysis of various policies. In Chapter 4, I discuss the policies applied in the model in greater detail, and present the results in Chapter 5. A conclusion, including the discernible policy recommendations, follows in chapter 6.

Chapter 2

Background

2.1 Aviation and the Global Economy

According to the 2002 Benchmark Input-Output table for the United States (BEA, 2008), as a share of total consumption, aviation is relatively small—less than 1% of U.S. GDP in 2002. But the commerce which aviation enables, combined with its unique capacity to provide high-speed intercontinental travel, makes aviation activities important to the structure of the economy. Business use of aviation, which is not counted in GDP, is a large part of aviation-sector output,[1] and as a mode of shipping, aviation is increasingly important. A study by Hummels (2007) finds that from 1965 to 2004 the value share of air transport in all U.S. exports excluding North America has grown to a total share of 52.8% in 2004, while the share for imports was 36.0% in 2000.

The increasingly important role of aviation in the global economy has been repeatedly demonstrated by econometric measurements of the income elasticity for demand of aviation which show a positive, greater-than-unity estimates. While in some markets, studies have made sub-unity estimates of income elasticity (Abrahams, 1983; Savage et al., 1995), the majority studies find that in general, greater amounts of aviation are consumed when income grows (Gillen et al., 2003; Taplin, 1980; Alperovich

[1] According to the 2002 Use Summary table (BEA, 2008), the value of intermediate (non-government, non-household) consumption of air transportation was 33.2% of total sectoral output.

and Machnes, 1994; Njegovan, 2006). In a meta-analysis of 139 individual estimates of income elasticity Gillen et al. (2003) find a median estimate of 1.39. Based on these elasticities forecasters predict a growing share of aviation in the global economy as incomes grow in the future: the FAA (2011) forecasts domestic revenue-passenger kilometers (RPKs) to more than double over the next 20 years, and ICAO (2008) forecasts total global RPKs of over three times higher over the same period.

2.2 Barriers to Growth

2.2.1 Fuel Prices

While demand for aviation has been growing, the increase in fuel prices over the last decade have substantially altered the cost structure for airlines. According to the IATA (2011), the price of jet fuel on April 8, 2011 was 3.91 times higher than the average price for 2000. With increasing fuel prices, the fuel share of airline operating costs has more than doubled in recent years. The IATA (2010) estimates that the share of fuel expenses as a percentage of total operating costs among all major world airlines more than doubled from 13.6% in 2001 to 32.3% in 2008. While 2009 data from the Bureau of Transportation Statistics (compiled by Swelbar and Belobaba) shows that among U.S. airlines this share declined to 27%, according to the United States Energy Information Administration (2011) average fuel prices for 2011 are expected to be even higher than 2008 averages.

2.2.2 Aviation Emissions

In addition to the problems of oil scarcity, airlines currently rely on technologies which produce climate damages through a number of mechanisms. Though emissions of CO_2 are currently unregulated, uncertainty about the costs of GHG emissions in future climate policies drive industry concerns of new costs with few mitigation opportunities (May, 2009a,b). Faced with these new constraints, stakeholders and policymakers are actively engaged in shaping the future of aviation.

Penner et al. (1999) project that over the next several decades, aviation will be one of the fastest-growing anthropogenic sources of greenhouse gases. While calculating aviation's share of total anthropogenic radiative forcing in 1992 at 3%[2] the IPCC estimates the total combined effects of aviation activities' warming will by 5% of global anthropogenic warming by 2050 (Penner et al., 1999; IPCC).

While carbon dioxide is the primary emissions product of concern, burning jet fuel produces many other gases and particles. Following the FAA (2005), emissions products and their mass shares are listed in Table 2.1. Carbon dioxide makes up about 70% of combustion products by mass. The balance of emissions are made up by water vapor (slightly less than 30%) and trace amounts of other gases (less than 1% each). Water vapor also acts as an atmospheric greenhouse gas, its direct contribution to warming is small. However, according to Penner et al. (1999), water vapor plays a direct role in almost all subsequent atmospheric chemistry, and in contrail and thin cirrus cloud formation. Of the remaining emissions products, the amount produced is very small relative to the total, and none act as directly as greenhouse gases though they are important pollutants for human health, and NO_x emissions specifically are important for their climatological effects as NO_x is a precursor to ozone. Significant industry and government effort to control emissions of carbon monoxide, sulfur oxides, non-methane volatile organic compounds, and particulate matters have had some success in reducing emissions (FAA, 2005; ICAO, 2009; Taylor, 2009). However according to FAA (2005), NO_x formation remains difficult to control. Bower and Kroo (2008) explain that engines have reached levels of efficiency where performance characteristics such as NO_x reduction and fuel efficiency exist as a trade-off.

[2] Initially the supplemental report, "Aviation and the Global Atmosphere" estimated the share of emissions at 3.5%. In the subsequent 4$^{\text{th}}$ assessment report, this figure was revised to 3%

Aviation Emissions Products		
Carbon Dioxide	CO_2	$\sim$ 70%
Water Vapor	H_2O	>30%
Nitrogen Oxides	NO_x	>1%
Volatile Organic Compounds	VOC	>1%
Carbon Monoxide	CO	>1%
Sulfur Oxides	SO_x	>1%
Particulates	BC, OC	>1%

Table 2.1: Emissions products of aviation and approximate mass fractions

Complicating the problem of aviation emissions is the difference between ground level emissions and emissions that occur throughout the troposphere. Penner et al. (1999) find that upper-tropospheric emissions of ozone precursors more efficient generators of ozone, and Barrett et al. (2010) conclude that through complex atmospheric chemistry cruising-altitude emissions could also be important contributors of surface-level pollutants. Finally, emissions of non-GHGs at cruising altitude may lead to the formation of thin cirrus clouds which trap heat and displace naturally occurring (and heat-reflecting clouds). Burkhardt and Karcher (2011) find that this effect may have a greater global-warming potential (GWP) than GHG emissions.

2.3 Technological Solutions

Aviation technologies in use are mature, and are the product of extensive research and development programs, but homogeneous in their reliance of kerosene-type jet fuel. Since its introduction the turbofan has undergone significant incremental improvements in fuel efficiency, but no new fuels have been introduced for use (Lee et al., 2001; Hummels, 2007). Unlike land and sea transportation, air transportation is marked by a distinct lack of alternate modes and very low diversity of power sources. Thus, while alternative fuels and powertrains, as well as alternative modes are relatively certain near-term alternatives for land transport, solutions in aviation are much more limited (GAO).

Alternative aviation fuel technologies include fuels bases on alternative fossil fuels (oil sands, Fischer-Tropsch fuels), fuels based on plant oils (either oxygenated 'bio-diesel,' or de-oxygenated hydroprocessed renewable jet; HRJ), and alcohol-based jet fuels. Hileman et al. (2009) find that only three are identified as likely near-term alternative fuels (next ten years): conventional jet fuel produced from oil sands, Fischer-Tropsch fuels from coal, natural gas (or potentially biomass), and HRJ from renewable oils. Only HRJ fuel comes from a renewable source, and according to Stratton et al. (2010), could potentially reduce net carbon emissions on a well-to-wake basis (the two alternative fossil fuels are likely to yield moderate to substantial increases in emissions), however estimates of the net emissions of each fuel type are highly sensitive to uncertainty about land use change. Unfortunately, land is a scarce resource, and biofuels are likely to compete with agriculture for arable land(Melillo et al., 2009). Furthermore, renewable jet fuel producers would have to compete with other renewable diesel producers for feedstocks, but compared to diesel fuel for land transport, aviation fuel must meet more stringent specifications, and therefore sees higher marginal costs (Hemighaus et al., 2004).

New airframes and materials have the potential to increase aircraft fuel efficiencies significantly, but according to Spitz et al. (2001), aircraft development cycles take a very long amount of time and current efforts to reduce the development cycle are not likely to meet their targets. Nonetheless, the GAO identifies the blended wing-body airframe (BWB), as an airframe that could deliver 33% efficiency gains over current airframes. Composite Materials are already included in several new airframes to a varied extent, notably in the Boeing 787 and the Airbus A380. Composites allow planes to be built lighter and stronger, and their continued integration into airframes is a source of future efficiency improvements. For example, large parts of the Boeing 787's fuselage and wings are built with composite materials which Boeing claimes reduces fuel use by 20% compared to the 767 (Hawk, 2005; Boeing).

Air Traffic Control Improvements have the potential to decrease congestion and delays, and allow more efficient flight paths. Delays in air travel lead to wasted fuel and wages, as well as mis-allocated capital. According to Robyn (2007) while congestion can result from weather delays, much is the result of a lack of capacity in ATC infrastructure. In order to address the lack of capacity and increase operational efficiency, the Federal Aviation Administration has begun a large, long-term systems upgrade program, collectively named NextGen (JPDO, 2007). These technologies include GPS-aided navigation, autonomous flight path coordination, digital communication between aircraft and ground-based navigation systems, improved awareness and handling of weather data, and automation of many ATC operations (JPDO, 2007). Proposed NextGen systems have significant potential to increase system-wide capacity, safety, and efficiency, including early tests which demonstrate the feasibility of airspace capacities three times the current level (Prevot et al., 2010). However the GAO (2010) states that quantifying the potential system benefits is difficult, as the FAA has yet to define specific goals or capabilities for long-term expansion efforts, let alone develop and test technologies.

2.4 Climate Change and Social Costs

The costs of climate change are large, global, and irreversible. Furthermore, due to the timescale and uncertainty over which climate damages will occur, comparison between the costs of climate outcomes, and the large, relatively near-term and certain costs of GHG mitigation is likely to produce results subject to intense political and academic scrutiny. The best-known example of a comprehensive, long-term cost-benefit analysis was presented in the 2007 report, "The Economics of Climate Change - The Stern Review." The Stern Review found that while marked by uncertainty, the costs of climate change outweigh the costs of mitigation (Stern, 2006). But dubious assumptions are necessary to come to this conclusion: rates of time-preference must be applied across multiple generations, calling the validity of a policy maker's agency into question, and uncertainty about climate impacts is compounded when considering the economic impacts of those future changes. Despite the ongoing debate over the outcomes and relevance of cost-benefit analyses of climate change mitigation (Weitzman, 2007; Yohe and Tol, 2007; Nordhaus, 2009), I proceed with a cost minimization analysis which seeks to reduce emissions on a lowest-cost basis while meeting some mitigation goal.

2.5 Policy Theory: Command & Control vs. Market-Based Instruments

Controlling an externality on a society-wide level can typically take one of two forms, both provided by a strong government actor: direct 'command and control' regulation, or market-based instruments designed to internalize the social cost of an externality. Economists concerned with maximizing social welfare typically prefer the latter for the economic efficiency gained, while through the political process, the former is often the result.

Emissions of Carbon Dioxide and Oxides of Nitrogen, as well as contrail cloud formation are economic externalities produced by aviation. Economic theory predicts that the lack of a price signal will lead to an over-production of the social "bad;" climate change (Hardin, 1968).The mechanism by which the overproduction of an economic externality may occur has become widely recognized as the main problem of environmental regulation. Society's inability to autonomously recognize and respond to the threat of climate change, and to therefore to act in its own rational self interest, belongs to a special class of market failures called collective action problems, discussed by Olson (1974). In a collective action problem, the greatest transaction cost comes from the potential for free-ridership, or an individual's incentive to "pretend to have less interest in a given collective consumption activity than he really has" (Samuelson, 1954). Samuelson claims that if a consumption good is not rivalrous, consumers will elect to pay less than the marginal cost of production. Market-based policy instruments seek to harness the equilibrating forces of supply and demand to resolve collective action problems. By assigning a real price to an economic externality, governments may internalize the marginal social cost, leading to an efficient allocation of consumption away from the social "bad."

By contrast, command & control policies include any policy which seeks to directly restrict the production of a social externality. Examples of such regulations include Corporate Average Fuel Economy (CAFE) standards for automobiles, energy efficiency and labeling standards for appliances (Energy Star), and quotas for minimum production of renewable fuels (Renewable Fuel Standard). But due to the global scale of the problem of climate change, targeted emissions reductions policies like these are likely to miss the lowest-cost marginal emissions reduction. A price on emissions would be the most efficient regulation, leaving the decision on how to minimize costs up to the most informed actor.

With the price of emissions internalized, the market mechanism can balance supply of and demand for emissions, and achieve a socially optimal outcome, but only if the price reflects the true social cost of emissions. While some attempts have been made to calculate a marginal social cost of GHG emissions (Group, 2010; Yohe et al., 2007), uncertainty is wide because costs hinge not only on uncertain physical parameters of climate outcomes and uncertain effects of climate damages on human welfare, but also on disagreements on how to value future damages in present terms.

Rather than formulating a marginal social cost of carbon, it is possible to restrict emissions to a certain level and allow a price to form endogenously by selling the right to emit. Given an idealized representation of the economy, quantity-based, or "cap and trade" policies can be shown to result in equivalent outcomes as a strictly price-based policy such as a carbon tax (Aldy et al., 2009). In practice, however, there can be significant differences between these types of policies including how each policy changes incentives as economic conditions change (Stavins and Whitehead, 1992).

2.6 European Union Emissions Trading System

The ETS is a pan-European Union policy which covers all large, stationary-source emitters, and requires permits for every ton emitted. Prior to inclusion of aviation, the policy regulates approximately 46% of EU CO_2 emissions (Wagner, 2004).The ETS is currently in its second phase which began on January 1, 2008 and will close in 2012. Within each phase, permits are tradable, and both banking (holding permits for use later) and borrowing (using permits from future allocations) are allowed (Ellerman and Joskow, 2008).

In 2008, the European Commission approved the inclusion of aviation emissions into the ETS, starting in 2012 (European Commission, 2008). The approved sectoral reductions are 97% below 2004-2006 emissions by 2012, and 95% below for 2013. The 2008 directive does not establish emissions quotas past 2013, but the recently release white paper on European Transportation seeks to reduce transportation sector emissions by 60% below 1990 levels by 2050 (European Commission, 2007, 2011). The European Commission has not clarified what reduction targets it expects for the aviation sector.

2.7 The Costs of Policy

Domestically, analysis of an economy-wide cap-and-trade policy similar to the "Waxman-Markey" bill (H.R. 2454, 111$^{\text{th}}$ congress)—a policy which would have reduced total national emissions to 68-87%[3] of 2005 levels by 2050— using the MIT Emissions Prediction and Policy Analysis (EPPA) model found that the policy would decrease welfare by 0.8% to 1.45% in 2050 compared to the baselinePaltsev et al. (2009b). Because it is a domestic policy, the emissions reductions in the Waxman-Markey bill cannot be extrapolated into a global GHG stabilization level, but the IPCC Fourth Assessment Report states that policies which result in a 535-590 ppm CO2-eq stabilization level are projected to cost 1.3% of GDP on average (IPCC, 2007).

[3]This range of reductions differs from the explicit policy goal of 17% of 2005 levels by 2050 because it does not count offsets as emissions reductions within the U.S. If offsets result in actual emissions reductions elsewhere in the world, the total emissions reductions as a result of the policy will be equivalent to the policy goal.

2.8 Aviation-Sector Policy Proposals

Proposals from airlines and industry associations have consistently sided against aviation's inclusion in economy-wide cap and trade policies. The U.S.-based Air Transport Association (ATA) and the China Air Transport Association have both opposed international flights' inclusion into the EU ETS (GreenAir, 2010; Cantle, 2011), and the ATA opposed aviation's inclusion in the 'Waxman-Markey' climate legislation in 2009 (May, 2009a,b). The IATA objects to aviation's inclusion in national climate policies as it sees the potential for a "patchwork" of national and trans-national climate regimes, and anticipates anti-competitive outcomes that prefer particular airlines based on their nationality, or double-counting of some emissions due to inconsistent international coordination (IATA, 2009). Instead, the IATA supports a global aviation-sector cap that limits aviation emissions to 2020 levels, and allow trading of emissions permits among all airlines from every region. Regardless of the efficacy or efficiency of such a policy, given the current state of international climate negotiations the approach is of questionable feasibility. Furthermore while under an economy-wide cap the efficient level of sectoral emissions would be determined endogenously, a sectoral cap opens the possibility of over- or under-estimation of the efficient level for the cap. If permits are auctioned, and if trading is allowed between the aviation sector and the economy-wide cap, then estimation of the sectoral cap is not a problem. If, however allocations are free, a separate sectoral cap which commits aviation to carbon-neutral free growth after 2020 will cost airlines the potential rents from free allocations.

Domestically, the ATA (2010) has identified a set of policy recommendations in its publication, *21st Century Aviation - A Commitment to Technology, Energy and Climate Solutions*. The ATA endorses the IATA goal of a global-sectoral emissions cap at 2020 levels, and likewise argues against domestic regulation. In opposition to aviation's inclusion in a domestic cap-and-trade policy, the ATA reasons that the recent rise in fuel costs provides sufficient incentive for airlines to mitigate emissions, and that further price increases would lead to decreased efficiency. There is some evidence to support the proposition by the ATA that increased fuel prices through climate policy would have a detrimental effect on fleet-wide fuel efficiency. In a previous study coupling the EPPA model with an aviation-specific partial equilibrium model, Winchester et al. (2011) find that under an economy-wide cap, declines in demand due to increased price and decreased income result in decreased investment in new aircraft and slower fleet turnover, which in turn results in worse fleet-average fuel efficiency compared to the baseline. Winchester et al. (2011) found that the policy-induced decline in efficiency ranged from 0.5% to 2.3% in 2050. However, while decreased efficiency may be considered suboptimal all else being equal, the objective of a cross-sectoral policy—to mitigate climate damages at the lowest social cost—may still be met by reducing emissions elsewhere in the economy, even if efficiency decreases in other sectors.

Chapter 3

Methodology

3.1 EPPA Background

The MIT Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic computable general equilibrium model that describes the global economy in 16 regions and with 15 economic sectors. EPPA for Aviation, or EPPA-A is a modified version of the fifth implementation of EPPA which adds the 15th sector: Air Transportation, highlighted in Table 3.1.

The most recent documentation available is for EPPA4, but the main structure of EPPA-A is unchanged from Paltsev et al. (2005). Changes in EPPA5 are primarily a change in the underlying data from the GTAP5 to GTAP7 data set (bringing the base year from 1997 to 2004), and the disaggregation of the agricultural sector in to crops, livestock and forestry. Labor force and productivity growth are also updated from the EPPA4 model according to the assumptions made in Paltsev et al. (2009a).

EPPA describes the economy in terms of nested Constant Elasticity of Substitution (CES) functions that relate the structure of inputs to both cost functions of producers and to the demand functions of consumers. EPPA-A adds a CES production structure for aviation, and alters the production of household transportation to include the new input.

EPPA-A Regions		EPPA-A Sectors	
USA	United States	CROP	Agriculture - crops
CAN	Canada	LIVE	Agriculture - livestock
MEX	Mexico	FORS	Agriculture - forestry
JPN	Japan	FOOD	Food products
ANZ	Australia - New Zealand	COAL	Coal
EUR	Europe	OIL	Crude Oil
ROE	Eastern Europe	ROIL	Refined Oil
RUS	Russia Plus	GAS	Gas
ASI	East Asia	ELEC	Electricity
CHN	China	EINT	Energy-intensive Industries
IND	India	OTHR	Other Industries
BRA	Brazil	SERV	Services
AFR	Africa	TRAN	Transport
MES	Middle East	CGD	Savings Good
LAM	Latin America	**AIRT**	**Air Transport**
REA	Rest of Asia	**HTRN**	**Household Transportation**

Table 3.1: EPPA-A Regions and Sectors

Production Structure

Production in EPPA-A closely follows production in the standard EPPA model. At the lowest level, all primary energy goods are aggregated into a primary energy input. This is nested with electricity to form a composite energy good. Energy is substitutable with the value-added nest which consists of capital and labor. The aggregate energy-value added nest is combined with other intermediate inputs which enter into the top-level Leontief nest. Intermediate goods can be composed of domestic or composite import goods, where the composite imports consist of a nest of imports from all other regions. EPPA-A's aviation production structure is displayed in Figure 3-1.

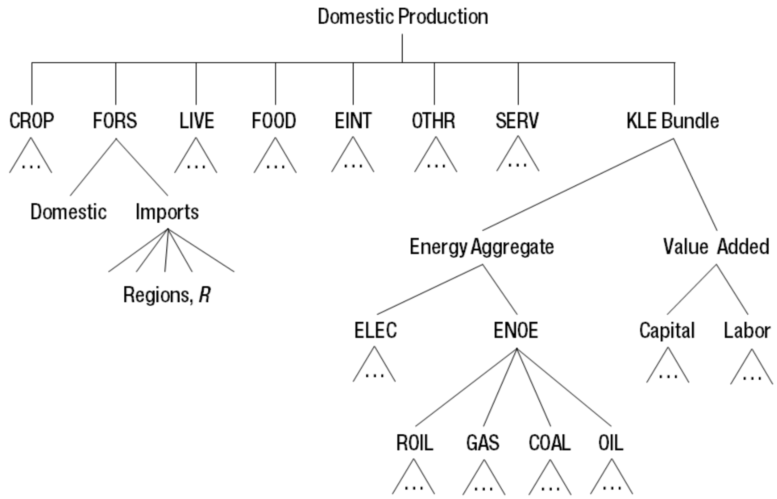

Figure 3-1: EPPA-A Production Structure for Aviation Sector

Consumption Structure

Like production, consumption in EPPA-A mirrors that of the standard EPPA model, except for the addition of Air Transport. At its lowest level, consumption is split between a composite energy good (that does not take account of the difference between electricity and primary energy), and non-energy goods. Non-energy goods include all non-transport, non-energy related goods. This composite ”other consumption” enters into the consumption nest with the composite transportation nest to form “total consumption.” Total consumption is substitutable for savings at the top of the nest.

The composite transportation good consists of purchased transport and owned-transport. Purchased transport is a composite of air transportation and other transportation, whereas owned-transport represents privately-owned cars and consists of an energy input (refined oil) combined with a nest that includes inputs from the “services” and “other” sectors. Consumption EPPA-A is displayed in Figure 3-2.

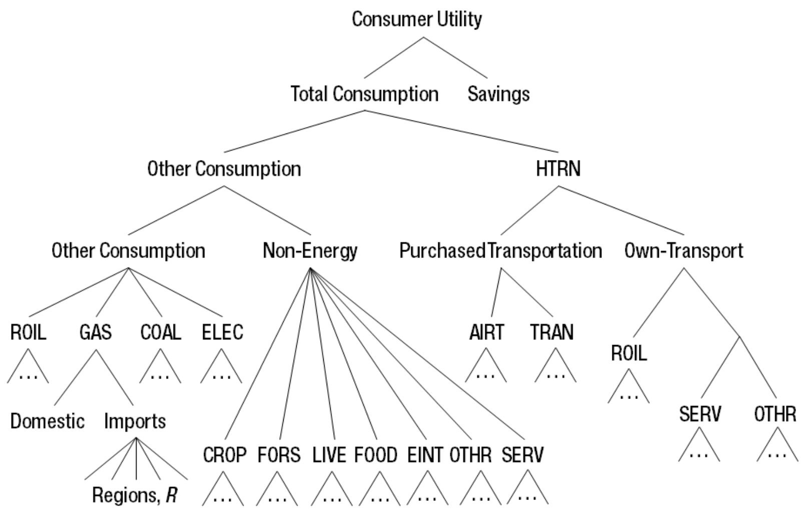

Figure 3-2: EPPA-A Consumption Nest

3.2 Calibration Data

Equilibrium and Data

Although the balanced GTAP7 database is essential for an equilibrium model, the process of balancing data undoubtedly results in noise at granular levels (for more information see the GTAP 7 documentation, Narayanan G. and Walmsley (2008)). In the case of civil air transport in the U.S., the GTAP7 data reports a total sectoral output of \$182.6 Billion. While GTAP 7 uses 2004 for the base year, the data for the U.S. is sourced from the 2002 U.S. input-output tables provided by the Bureau of Economic Analysis, and scaled forward to 2004. The 2002 input-output tables report a sectoral output of \$102.4 Billion, a difference of almost 80% in two years (BEA, 2008). To confirm the discrepancy, data from the Air Carrier Statistics database (form 41 data) is presented below in Table 3.2 for both 2002 and 2004 (U.S. Bureau of Transportation Statistics, a).

In order to give a more accurate picture of the U.S. aviation sector, the GTAP7 database is rebalanced according to the air transport sector output given by the 2004 Air Carrier Statistics form 41 data.

Disaggregation of sector

The first step to re-balancing the GTAP data is to aggregate it into EPPA regions and sectors. Whereas air transport exists as a standalone sector in the GTAP 7 data set, the default EPPA aggregation scheme combines aviation into the transport (TRAN) sector. The difficulties presented in disaggregation of aviation from other transportation are minimal. GTAP includes separate accounting of air transportation (atp), water transportation (wtp), and all other transportation (otp). In the standard EPPA model, these three GTAP sectors exist as one EPPA sector, TRAN. A standalone air transport (AIRT) sector is created by removing atp from TRAN and assigning it to AIRT.

Sector Calibration

The preliminary step of creating an air transport sector complete, the benchmark economic data must be balanced with a new starting value for aviation output. In addition to adjustments to total output, a share of aviation is shifted from intermediate demand by the services (SERV) sector toward final demand. The BEA Use table indicates that almost 70% of domestic aviation consumption is final demand, whereas GTAP allocates the lion's share to SERV.

To re-balance the model after making the above changes, a non-linear programming approach is used. The Social Accounting Matrix (SAM) which contains the base-year data must meet the conditions set forth above. In addition, there are region-specific conditions which must be met. A 'least-squares' objective is minimized according to Equation 3.1

Source	**Output ($Billion)**	**Year**
BEA Input-Output Use Table	102.4	2002
Air Carrier Statistics Database	107.1	2002
Air Carrier Statistics Database	134.7	2004
GTAP7	182.6	2004

Table 3.2: Benchmark Sector Output and Sources

$$lsqobj = \sum_x [x_0(\frac{x}{x_0} - 1)^2] \tag{3.1}$$

Where x is the set of parameters in the benchmark data, with an initial value x0, and a variable value x. Lsqobj is minimized while satisfying the balancing conditions. The full matrix re-balancing code can be found in Appendix A.

3.3 Elasticity Parameter Estimates

3.3.1 Income Elasticity of Demand

Though the income elasticity of demand for air transport, η_A is important for forecasts of aviation demand growth, the existing EPPA framework does not allow an easy augmentation of income elasticities other than 1. This is because EPPA makes use of constant elasticity of substitution production and consumption functions with constant returns to scale that imply an income elasticity of demand equal to one. Using the time evolution of EPPA to augment growth allows exogenous forcing of a non-unity η_A.

Sources of Estimation

A large meta-study of aviation demand related elasticities was conducted by the transport and tourism consulting firm InterVISTAS (2007), which concludes "virtually all [the] studies estimated income elasticities above one, generally between +1 and +2." Jost (2010) provides an analysis of these studies and the applicability of their results for modeling, and finds that 1.4 is an appropriate world-wide parameter. In order to apply these results to EPPA-A, however, conclusions must be drawn about different markets, both those mature and growing. In the 2008 Travel and Tourism Competitiveness Report from the World Economic Forum, Blanke and Chiesa (2008) find that income elasticity is highest for developing countries, and declines as incomes increase and markets mature. They provide another reading of the InterVISTAS study which gives ranges of income elasticity across route and economy types. For the baseline η_A, 1.4 is chosen.

Method of Implementation

The CES functional form gives outputs that grow in income at a rate of unity. Increased growth based on a non-unity income elasticity of demand in total consumption, η_A, requires modifications to the demand function. Following Fullerton (1989), one approach is to add a displacement term, b, to the factor input in the CES function, and tune the displacement term such that changes in income are met by changes in demand for air transportation, AT, according to η_A. Using the CES nest for consumption of purchased transportation from Figure 3-2, $PURTRN$ is a composite of AT and other purchased transportation, OT. The total amount of $PURTRN$ is calculated from the inputs AT and OT, the share parameters, a_{AT} and a_{OT}, and the substitution elasticity, σ.:

$$PURTRN = [a_{AT}^{\frac{1}{\sigma}}(AT + b)^{\frac{\sigma-1}{\sigma}} + a_{OT}^{\frac{1}{\sigma}}OT^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \tag{3.2}$$

In the base year, it is possible to solve for b as a function of total output of air transport; AT, total income; I, the income elasticity of demand; η_A, and disposable income, I_D ($I_D \equiv I - p_{AT}b$). The solution provided by Fullerton (1989) yields:

$$b = AT(1 - \frac{\eta_A I_D}{I}) \tag{3.3}$$

This approach allows for endogenous adjustments to consumption of a good based on non-unity income elasticity, but only given a unity pricing assumption. If prices are not benchmarked to 1, the solution does not hold, and price effects dominate. I adapt the method for use in a dynamic model by adding a displacement term to the share parameter, a_{AT}, instead of the input AT. Adjustments are made to the share parameter following each period rather than endogenously. While using the dynamic process does not allow for intra-period income changes, the inter-period changes to income (driven by growth in labor force and productivity) dominate the intra-period changes. Thus, $PURTRN$ is formulated as follows:

$$PURTRN = [a_{AT}^{\frac{1}{\sigma}}AT^{\frac{\sigma-1}{\sigma}} + a_{OT}^{\frac{1}{\sigma}}OT^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \tag{3.4}$$

And rather than adding the displacement coefficient b to the factor input, it is added to the input share parameters a_{AT} and a_{OT}. Both share parameters must be re-normalized according to the displacement, and are functions of initial-period consumption of air transportation AT_0, other purchased transportation, OT_0, and the displacement term, b:

$$a_{AT} = \frac{AT_0 + b}{AT_0 + OT_0 + b}, \qquad a_{OT} = \frac{OT_0}{AT_0 + OT_0 + b} \tag{3.5}$$

Assuming the elasticity of substitution, σ, is approximately one, the change in demand for air transportation due to the displacement is approximately equal to the displacement:

$$b \approx \Delta AT \tag{3.6}$$

The definition of income elasticity, η_A is as follows:

$$\eta_A = \frac{I}{\partial I}\frac{\partial AT}{AT} \tag{3.7}$$

Recognizing that η_A is composed of endogenous income growth at a rate of unity, and an additional rate which is forced exogenously, η_A can be decomposed into $\eta_{A,E}$ and 1. Likewise, change in demand can be decomposed into change due to endogenous growth, ΔAT_e, and change in demand due to input share displacement, b, it is possible to back-solve for displacement:

$$b = \frac{AT\Delta I}{I}(\eta_{A,E} + 1) - \Delta AT_e \tag{3.8}$$

Which reduces to:

$$b = \frac{AT\Delta I}{I}\eta_{A,E} \tag{3.9}$$

This expression leaves the displacement as a function of total consumption, change in total consumption, and demand for air transportation, all of which are readily available within the model.

3.3.2 Substitution Elasticities

The majority of substitution elasticities in EPPA-A are unchanged from the EPPA 5 model (Paltsev et al., 2005). This includes the elasticities in the cost function for production of aviation, with the exception of the elasticity of substitution between energy and the value-added nest, $\sigma_{E,KL}$, which has the most direct effect on the rate of endogenous technical efficiency improvement available to the aviation sector. Unlike AEEI, endogenous efficiency is the result of price signals influencing change in the production structure. The vast majority of aviation-sector energy use (>98%) is refined oil consumed by aircraft. Because of the technical homogeneity of the sector, and the relatively long life of planes in the fleet, this elasticity is likely to be low, but it is also difficult to directly measure. Historical rates of total energy efficiency improvement in the aviation sector provide one potential source of calibration. There are several published estimates, and it is possible to adjust $\sigma_{E,KL}$ so that the BAU total energy efficiency improvement rate aligns with these estimates (Lee et al., 2001; Penner et al., 1999). Nest elasticities are given in Table 3.3.

Production		**Consumption**	
$\sigma_{D,M}$	3.0	$\sigma_{C,S}$	0.0
$\sigma_{M,M}$	5.0	$\sigma_{C,T}$	0.5
$\sigma_{E,KL}$	0.1	$\sigma_{P,O}$	0.4
σ_{VA}	1.0	$\sigma_{A,O}$	varies
$\sigma_{E,NOE}$	0.0		
σ_{EN}	0.0		

Table 3.3: Nest Elasticities for Aviation

3.3.3 Own-Price Elasticity of Demand

Like the income elasticity of demand, EPPA does not explicitly use an own-price elasticity of demand for each sector. Instead, the own-price elasticity is expressed as a function of the value shares (in total cost) and elasticities of substitution in the intervening consumption nests. Whereas the own-price elasticity of demand can be straightforwardly estimated econometrically, substitution elasticities are specific to

Market Segment	**Min**	**Mean**	**Max**
Long-Haul International Business	-0.475	-0.265	-0.198
Long-Haul International Leisure	-1.7	-1.04	-0.56
Long-Haul Domestic Business	-1.428	-1.15	-0.836
Long-Haul Domestic Leisure	-1.228	-1.104	-0.787
Short-Haul Business	-0.783	-0.7	-0.595
Short-Haul Leisure	-1.743	-1.52	-1.288

Table 3.4: Own-Price Elasticities from Gillen et al. (2003)

individual models, and directly applicable estimates are rare. Therefore, substitution elasticities are determined based on econometrically measured own-price elasticities and value shares from the benchmark data.

There is a large base of literature estimating the own-price elasticity of demand for aviation econometrically, including two recent and comprehensive meta-studies. Gillen et al. (2003) compile 21 unique econometric studies of the own-price elasticity of demand for air transportation, rank them, and synthesize the parameters, applying three dichotomies, resulting in six categories they find essential for the description of air transport markets. These markets are defined by the distinctions between: Short Haul vs. Long Haul, International vs. Domestic, and Leisure vs. Business travel. Results from Gillen et. al. are summarized in Table 3.4.

In EPPA-A these market distinctions are not used. Instead a single aggregate own-price elasticity of demand is used to calculate the elasticity of substitution. Across all market distinctions, the price elasticity of demand is shown to be negative, and the average elasticity across all markets is -0.96, which is rounded up to -1.

Application of Own-Price Elasticity of Demand

In EPPA-A, aviation is directly substitutable with other purchased transportation. This sector includes all transportation goods which are not air transportation, or road transportation using self-owned vehicles. The elasticity of substitution between air transport and other purchased transport can be adjusted so that the own-price elasticity of demand for aviation matches the estimate. According to Tyers and Yang, the own-price elasticity of demand, $\eta_{A,A}$ can be expressed in terms of these parameters

EPPA Region	$\sigma_{A,O}$
USA	1.27
CAN	1.33
MEX	1.07
JPN	1.10
ANZ	1.43
EUR	1.23
ROE	1.05
RUS	1.11
ASI	1.26
CHN	1.05
IND	1.04
BRA	1.16
AFR	1.15
MES	1.16
LAM	1.12
REA	1.16

Table 3.5: Elasticity of Substitution by region

according to the following formula, where θ_i is the share of sector (or aggregate good) i in total consumption, and σ_{ij} is the elasticity of substitution between sectors i and j (Tyers and Yang, 2000).

$$\eta_{A,A} = -\theta_A[\sigma_{A,O}(\theta_A^{-1} - \theta_O^{-1}) + \sigma_{O,T}(\theta_O^{-1} - \theta_T^{-1}) + \sigma_{T,C}(\theta_T^{-1} - \theta_C^{-1}) + \sigma_{C,S}(\theta_O^{-1} - 1)] \quad (3.10)$$

In order to implement an own-price elasticity of demand consistent with the literature estimates, the elasticity of substitution between air transport and other purchased transportation, $\sigma_{A,O}$ is adjusted. Because share parameters vary across regions, so too must $\sigma_{A,O}$ take region-specific values. These are reported in Table 3.5.

3.4 Other Model Features

Autonomous Energy Efficiency Improvement

Autonomous energy efficiency improvement is applied to most sectors of the economy based on an exogenous parameterization of the historical changes in non-price induced declines in the share of energy in consumption. The need for this factor arises from econometric data which shows that over time economies become more efficient at a rate greater than that which can be explained by prices, and is often ascribed to non-price induced technological change. In EPPA-A, rates of autonomous energy efficiency improvement are based on those in EPPA4, and are varied across regions, with developed economies and China seeing the highest rates of improvement, and developing economies lagging behind (Webster et al., 2008; Kaufmann, 2004; Paltsev et al., 2005). Due to the small number of commercial aircraft manufacturers, aviation is assigned a rate that is constant across all regions and consistent with developed economies.

In the aviation sector, higher annual rates of fuel efficiency improvement have been assumed (1.4% by the IPCC (Penner et al., 1999), 1.2-2.2% by Lee, et. al. (Lee et al., 2001)). However, these studies have estimated rates of potential technical change given past prices. Since fuel costs are a significant portion of airlines' cost structures, there is likely to be additional price-induced technical change.

Biofuels

EPPA-A includes sectors for the production of 2nd generation biofuels based on the incremental costs of cellulosic ethanol. The sector produces a substitute for refined oil products, but is disallowed for use in aviation.

Emissions and Fuel Use

EPPA tracks fuel use in physical units according to the method in Paltsev et al. (2005), which allows direct calculation of a sector's physical carbon emissions based on the carbon content of the fuel used. CO_2 emissions are calculated from the carbon content of each type of fuel. While aviation emissions of non-CO_2 greenhouse gases are negligible, under the cap, trading between gases is allowed according to the 100-year global warming potentials (GWP) in Table 3.6.

Species	GWP
CO_2	1.00
CH_4	5.72
N_2O	84.47
PFC	1,771.12
SF_6	6,512.26
HFC	354.22

Table 3.6: 100-year Global Warming Potential

EPPA-A also calculates and reports emissions of urban gases including carbon monoxide (CO), non-methane volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and black and organic carbon (BC, OC). These gases evolve according to trends described in Paltsev et al. (2005). Base-year aviation emissions of criteria pollutants are disaggregated from the totals in the TRAN sector according to their fraction in the Emission Database for Global Atmospheric Research (EDGAR) 3.2FT2000 database (Olivier et al., 2005).

3.5 Alternative Aviation-Specific Modules

3.5.1 Air Traffic Control Improvements Module

In order to highlight the potential emissions reductions possible from future efficiency gains in the national air traffic control (ATC) system, an additional module is introduced. New ATC infrastructure is represented as a perfect substitute for the portion of the production nest which represents flight operations. The availability of ATC goods are limited by the production of "ATC Services" by the government for each period, which itself is equal to the cumulative amount of advanced ATC taxes collected in the previous periods, times a markup. The scale of production is not driven by relative prices, but fixed so that the total amount of cumulative ATC tax revenue, and only as much, is converted into ATC services. The taxes begin in 2015 and carry through to either 2025 or 2035, with subsequent taxes equal to the benchmark depreciation rate. Cumulative revenue determines the scale of ATC output and is also subject to depreciation at the benchmark rate of 5%. Figure 3-3 shows the modified air transport production structure.

While published estimates vary widely, the tax rate and markup are tuned to reflect an amount of ATC services possible from the FAA's NextGen capital program. This structure offers several advantages, but is different from the typical EPPA-A production function. First, it reflects the real-world relationship between the provision and consumption of ATC services. In the U.S., ATC services are a good provided by the government to the airline free of charge, while the cost of the service is paid by taxes on the consumption of air transportation. Passenger taxes are ad-valorem, with a rate set by law, so the revenue depends on the quantity of air traffic control consumed, but the tax also increases the price of consumption. The choice to tax or not to tax is not a market decision, nor is the rate optimized for efficiency. In the standard EPPA-A model, passenger taxes are included in the benchmark tax rate, and the provision of ATC services is included in government consumption, and implicitly provides the same level of service throughout the model horizon; capacity is implicitly constant. With the addition of the ATC module, additional taxes are applied in order to improve performance above the baseline. The markup reflects the expected returns from real-world investments of this type, but due to a lack of certainty in the specific technologies to be employed in the NextGen build-out, compounded by uncertainty with respect to the potential costs of and savings available from these technologies, a large range is unavoidable. Markups are therefore estimated according to high, middle and low estimates for system efficacy. These estimates reflect the highest and lowest literature values found, or, as in the case of "percent of delays mitigated" where only one literature estimate was found, simply represent a large range around the center. Assumptions are made about the costs of delays to airlines in wasted fuel, labor and capital assignments, about the per-period costs of the NextGen system and about the ability of new technologies to reduce delays.

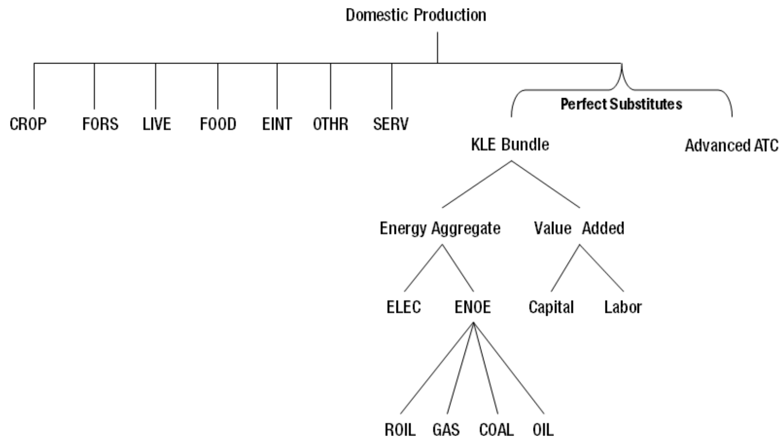

Figure 3-3: Advanced ATC in Production of Air Transport

Costs of Delays

The total economic costs of airline delays includes costs to airlines of wasted resources, costs to passengers of wasted time and loss in demand for aviation. Costs to airlines stem from wasted fuel and additional wages paid to staff as well as unnecessary capital use. These inputs to production are explicitly modeled in EPPA-A's energy-value-added nest, and are therefore can be displaced by ATC services. Costs to passengers, however, are not explicit inputs in EPPA-A, but reflect a cost to consumers equivalent to the lost value of time. These loses rely on econometric estimates of the value of time, and are not included in the estimates of potential savings to airlines. Various studies have estimated the size of each of these costs differently. In Ball et. al., the costs to airlines are found to account for roughly 30% of total economic costs, or $8.3 Billion (Ball et al., 2010). By comparison, a study by the Congressional Joint Economic Committee (JEC) finds double the cost ($19 Billion) to airlines, whereas lost passenger time was proportionally less ($12 Billion) (Joint Economic Committee, 2008). Both reports estimate costs in 2007, and are used as upper and lower bounds, with their average as the central estimate, for the costs to airlines of delays. To estimate the total cost of delays to airlines, the dollar cost in 2007 is normalized to the base year (2004) by the total average delay rate (from the

U.S. Bureau of Transportation Statistics (b)) and operating expenses in 2007 (from Swelbar and Belobaba) as a percentage of total expenses, and is presented in Table 3.7 (U.S. Bureau of Transportation Statistics, b; Swelbar and Belobaba). As mentioned above, this method assumes a constant percentage of flights delayed in future periods.[1]

Estimates of the Cost of NextGen Programs

While some NextGen programs are well-defined, others are less certain, particularly in the long-term where project capabilities are still being discussed. While near-term expenditures are focused on research and development, the model should reflect the costs of service provision. For estimates of program cost, the most recent estimates for both cost and program horizon from the Government Accountability Office are used. The costs of NextGen program implementation include government expenditures as well as airline capital upgrades. Because the equipage upgrades for airlines are required, providing for their cost with a ticket tax is identical to the airlines passing the costs through in the aviation price. Therefore, the government and airline capital costs are aggregated into a single program cost. The Government Accountability Office highlights the Joint Planning Development Office's (JPDO) estimate that the highest level of program performance could cost the FAA and airlines together over $160 Billion if implemented by the program horizon of 2025, while noting the costs could come down if the project horizon were extended to 2035 (GAO, 2010). This is a significant increase over previous JPDO cost estimates through 2025 of $29-$42 Billion, and it reflects the large uncertainties associated with the program's goals and their costs (JPDO, 2007).

For the ATC module, the lower bound for program cost is $40 Billion through 2025, and the upper bound is $160 Billion over the same period. The central estimate is $80 Billion through 2025.

Estimates of Delay Reduction

[1]According to the U.S. Bureau of Transportation Statistics (b), the total delay rate in 2007 was 26%; the highest rate on record. In the EPPA-A base year (2004), the total delay rate was 21.3%, whereas the average delay rate over the record provided by BTS (2002-2011YTD) was 20.7%. Therefore, the costs of delays as a percent of total operating costs in 2007 are adjusted by the lower average delay rate in the model.

The goals of NextGen infrastructure investments are many, but capacity expansion and delay reduction are instrumental toward decreasing airline costs. While it is working toward tripling airspace density, the JPDO has not made clear what level of delays will be acceptable under the NextGen system. Winchester et al. (2011), who use 2015 as the introduction of incremental efficiency gains in the U.S., and 2025 as the date of full system availability, simulate delay reductions by decreasing route distance across all flights by a fixed percentage. Instead, in EPPA-A, a fixed percentage of delay costs are eliminated. Because delay costs are assumed to be a fixed percentage of operating costs, the delay reduction is multiplied by the delay costs. For the central estimate, EPPA-A uses a 50% reduction in delays (following the estimate in Dray et al. (2010)). The reduction of fuel, capital and labor usage costs resulting from the use of the central estimate approximately accords with the reduction of costs which would result from the 10% reduction in distance in Winchester et al. (2011). The upper and lower bounds are 90% and 10% respectively. A complete set of high, low and central parameter estimates are included in Table 3.7.

	High	**Central**	**Low**
Baseyear Costs of Delays ($Billion)	15.35	11.03	6.70
Cost of Delays (% of output)	11.78%	8.47%	5.14%
Total Cost of NextGen ($Billion)	40	80	160
Program Horizon	2025	2025	2025
Cost Per-Period ($Billion)	13.3	26.7	53.3
Percent Delay Reduction	90%	50%	10%
Markup in Base Year	**1.03**	**0.21**	**0.01**

Table 3.7: Advanced ATC Markup Estimates

Because EPPA-A relies on a zero-profits assumption, industry output is equivalent to industry costs, and therefore, the savings to airlines in period t, SA_t, are defined by the industry output, AT_t, the cost of delays as a percent of output, $\%CD$, and the percent of delays mitigated by the ATC infrastructure $\%DR$:

$$SA_t = \%DR \times \%CD \times AT_t \tag{3.11}$$

The markup MU_t is the ratio of the savings to airlines to the exogenously-determined per-period program cost estimates in Table 3.7, PC_t:

$$MU_t = \frac{SA_t}{PC_t} = \frac{\%DR \times \%CD}{PC_t} \times AT_t \tag{3.12}$$

The program cost is also used to calculate a tax rate, τ_t, for each period based on industry output:

$$\tau_t = \frac{PC_t}{AT_t} \tag{3.13}$$

3.5.2 Business Management Variability

In addition to ATC improvements, potential fuel savings from management decisions that can affect the production functions using vintage capital are explicitly modeled. While the standard EPPA vintage production structure allows no substitutability between any inputs (all nest elasticities, σ=0), the business management modification allows airlines some limited substitutability between the energy and value-added nests (σ=0.1).

3.6 Sensitivity Analysis

All modeling comprehends some level of uncertainty. In economic modeling, it is particularly important to identify the relevant parameter estimates which may have the largest effect on model output. While previous studies of EPPA have explored the topic further, it is useful to have a method of comparing the impact of uncertainty around aviation parameters with that around other important EPPA parameters.

Tornado Diagrams

In order to assess the impact that different parameters will have on different outcomes, Tornado Diagrams are generated. The particular parameters of interest are those from EPPA which have been determined by Cossa to have the greatest effect on model outputs, with the addition of the air transportation AEEI rate. EPPA parameters are varied according to high and low values which were estimated to represent two standard deviations' difference through expert elicitation (Cossa, 2004). These parameters and their variations are listed in Table 3.8.

Parameter	**Low**	**High**
Vintage Share	-33%	+100%
Energy Nest Elasticity	-25%	+25%
AEEI Rate for All Sectors	-30%	+35%
AEEI Rate for Aviation	-30%	+60%
Labor Productivity	-20%	+20%
Aviation Income Elasticity of Demand	-15%	+15%

Table 3.8: Sensitivity Analysis Parameter Variation

The elasticity between energy and non-energy goods in production of agriculture as referenced by Cossa (2004) is not the same as the elasticity between energy and the value-added nest in air transportation, however the percentage range applied to the parameter (±25%) can be used. Another aviation-specific parameter which merits testing is the income elasticity of demand for aviation which ranges between 1.2 and 1.6 (±15%).

Chapter 4

Policies Implemented in this Study

In order to evaluate the response of the aviation sector to policy constraints, several policies are designed and compared to an unconstrained BAU case. In each carbon policy, exogenous emissions targets are set as fractions of 2005 emissions, and are applied in all Annex B regions from the Kyoto Protocol (UNFCCC, 1998). Additionally, advanced Air Traffic Control is applied in the U.S., and the business management model is applied in all regions. Table 4.1 summarizes the policies applied in this thesis.

Scenario	Name	Economy-Wide Cap	Aviation Sector Cap	Regions	Notes
Business As Usual	BAU			All	No emissions constraints in any Region
Economy-Wide Cap & Trade	POL	•		Annex B	Emissions constrained to 50% of 2005 levels by 2050
Aviation-Sector Cap with Trading	SECPOL_T	•	•	Annex B	Aviation emissions unconstrained until 2020; afterwards capped at 2020 levels. Aviation can purchase permits from other sectors
Aviation-Sector Cap without Trading	SECPOL_NT	•	•	Annex B	Aviation emissions unconstrained until 2020; afterwards capped at 2020 levels. Aviation cannot purchase permits from other sectors
Advanced Air Traffic Control	ATC			U.S.	Central, Low and High parameter estimates; applied to both BAU and POL
Business Management	VMGMT			All	Applied to both BAU and POL

Table 4.1: Policies Implemented in this Thesis

4.1 Business as Usual

In the business as usual scenario, the model is run from the base year of 2004 to 2050 with no emissions caps. While "business as usual" can imply assumptions about future policy decisions, in this case the BAU scenario is unconstrained by any existing policies, including the EU ETS. Model evolution is driven by the model structure and exogenous growth parameters, but limited by the fixed stock of land and fossil fuels.

4.2 Economy-Wide Cap & Trade Policy

Given the political uncertainty surrounding the state of greenhouse gas regulation in the developed world, and particularly in the U.S., no attempt is made to model any specific policy proposal. Instead, a generalized form of policies such as the EU Emissions Trading Scheme and the proposed 'Waxman-Markey' bill is applied. The POL scenario restricts the quantity of emissions of greenhouse gases according to a specific schedule. The policy covers CO_2 and all Kyoto Accord gases, which are tradable according to their 100-year global warming potentials (see Table 3.6). The policy applies Kyoto Accord Annex B regions. In EPPA-A these regions are the US, Canada, Russia, Japan, and the composite regions of Europe (including EU member states as well as other European Community members) and Australia-New Zealand.

Reduction schedules in the sample policy scenario follow a linear path starting with a cap of 95% of 2005 emissions in 2010, and reducing to 85% of 2005 emissions in 2015, and reducing 5% per period (1% per year) thereafter. The policy reaches a final cap of 50% of 2005 emissions by 2050. Because this is a hard cap with no offsets or global trading allowed, the final emissions reduction achieved in the U.S. is somewhat below the reductions achieved in the medium offsets case in an EPPA assessment of H.R. 2454 (Paltsev et al., 2009b). The reduction path of the sample policy compared to baseline in the U.S. is shown in Figure 4-1.

International trade is not regulated under the policy caps. While EPPA-A does not allow perfect substitution for either imports for domestic goods, or among imports from various regions, substitution is relatively elastic. While systems like the EU ETS anticipate border adjustments for inbound aviation, it is not clear that this will be the case for other national arrangements. In EPPA-A imports of aviation are regulated under the emissions policy of their origin, and exports are regulated under the domestic policy.

4.3 Sectoral Caps

Two sectoral caps are applied to EPPA-A: SECPOL_T, and SECPOL_NT. In both scenarios, the economy-wide cap is still enforced, but an additional aviation-sector-only cap is applied to airlines. The first policy, SECPOL_T, allows trading between the aviation sector and other sectors under the economy-wide cap. SECPOL_NT does not. Neither cap allows international trading, but both are applied in all Annex B regions. Under the sectoral cap, aviation sector emissions are allowed BAU growth until 2020. Afterwards emissions are capped at 2020 levels for all future periods. The 'carbon-neutral' growth of the aviation sector is complemented by an economy-

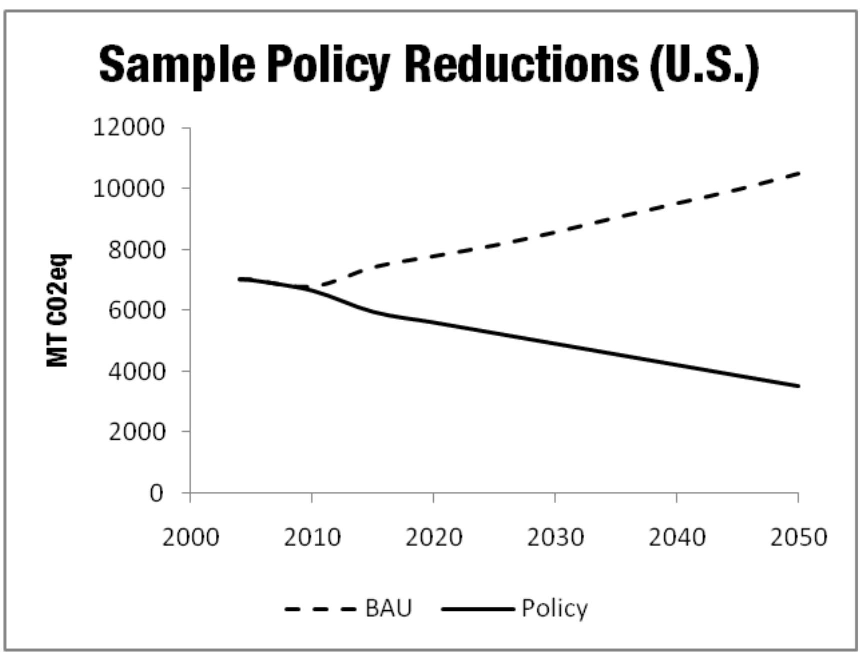

Figure 4-1: Sample Policy Emissions Reductions

wide cap identical to the above scenario, except for the exclusion of aviation from trading sectors. The quantity of aviation emissions is subtracted from the economy-wide cap so that the total national emissions remain identical in each policy case: POL, SECPOL_T and SECPOL_NT. The only difference between these three cases is the allocation of emissions caps. Trading between gases is permitted in the economy-wide cap, but because non-CO2 GHG emissions from aviation are approximately zero, there is no trading between gases in the sectoral cap. Under the sectoral cap with trading, the aviation sector can purchase emissions permits from other sectors under the economy-wide cap, but cannot sell aviation-cap emissions to other sectors of the economy.

4.4 Alternative Emissions Reduction Scenarios

The rate of energy efficiency improvement has a large effect on the evolution of aviation prices and sectoral growth. As the uncertainty analysis makes clear, changes in the rate of autonomous technical change have a large impact on not only the growth of the sector, but also on the sector's response to growing fuel prices. Further improvements in efficiency are available through endogenous substitution away from energy goods in the aviation sector's production cost function. In reality, however further non-market improvements are available due to technical improvements in air traffic control performance. Because these are not determined by the aviation sector, the BAU scenario does not explicitly account for NextGen systems except for their ability to keep pace with capacity growth. The BAU case implies a constant rate of delays across all periods.

The ATC case uses an alternative approach and models an explicit "Advanced Air Traffic Control" sector which, in addition to AEEI and endogenous efficiency improvements, increases the efficiency of air transport production. While uncertainties are large, the explicit accounting of advanced ATC technologies tests the importance of the effect of non-market infrastructure on the aviation sector's response to climate policy. The ATC case is applied as an add-on to both the BAU and POL cases, and is tested with central, low and high markup estimates (see Table 3.7). The ATC modification is only applied in the U.S.

Additionally, the model's handling of old airframes is adjusted to allow for a small amount of endogenous substitution away from energy use in older aircraft. This substitutability is meant to represent management variables which are not represented explicitly by the existing production structure. The VMGMT case is applied to the BAU and POL cases in all regions.

Chapter 5

Results

5.1 Business as Usual

EPPA-A yields a business as usual forecast for aviation growth through 2050. The BAU growth path affects the costs of policy scenarios presented below and is therefore discussed in some depth, and compared with similar aviation forecasts. EPPA-A's BAU scenario presents a world with significantly greater amounts of aviation in 2050, both globally and in the U.S. EPPA-A tracks both physical output of the various economic sectors, and the relative prices of commodities. Because EPPA models the economy with all quantities in dollar values, sectoral output is measured in dollars. Sectoral output in 2050 at 2004 prices is \$476 Billion in the U.S.; 3.66 times larger than the base year, 2004. This amount represents real output, and is best understood as a quantity of air transport services provided. Globally, growth is even more robust, growing from a total global sectoral output at 2004 prices of \$516 Billion to \$2.87 Trillion in 2050; 5.56 times larger.

EPPA-A forecasts slower growth over the period 2010-2030 than does the latest published FAA Aerospace Forecast (FAA, 2011). While the FAA forecasts an average annual rate of 3.1% growth in Revenue Passenger Miles (RPMs) for domestic markets over the period from 2010-2031, and an average annual growth rate among U.S. flag international RPMs of 4.8%, EPPA-A shows an average annual growth of sector output (including domestic operations, as well as international operations by U.S.

	Global		U.S.	
Forecast	2010-2035	2006-2036	2010-2030	2010-2031
EPPA-A	3.4%	∼	2.6%	∼
ICAO	∼	4.8%	∼	∼
FAA	∼	∼	∼	3.6%

Table 5.1: EPPA-A growth rates compared to forecasts

carriers) of 2.6%. This compares to the aggregate average FAA forecast of 3.6% growth from 2010 through 2031. The FAA assumes an average annual real Gross Domestic Product growth rate of 2.7%, while EPPA-A assumes a lower average annual GDP growth rate of 2.3% over the same period.

Globally, EPPA-A can be compared to the International Civil Aviation Organization (ICAO) Committee on Aviation and Environmental Protection's most recent global traffic forecast from 2006 to 2036 (ICAO, 2008). The ICAO forecast provides, like the FAA, expected annual rates of traffic growth, but segmented into three decadal periods. Also like the FAA, ICAO forecasts are more bullish than EPPA-A, projecting an average annual global RPK growth rate between 2006 and 2036 of 4.8%, where EPPA-A forecasts a growth rate between 2010 and 2035 of 3.4%.[1] These results are summarized in Table 5.1.

In addition to traffic forecasts, EPPA-A's BAU revenue forecast can be compared to the Aviation Environmental Portfolio Management Tool for Economics (APMT-E) results for BAU growth. While in the base year, output of aviation is equivalent to revenue because all prices are normalized to 1, for future periods, EPPA-A output must be multiplied by the normalized price of aviation. Where physical output is AT, revenue is R, and the relative prices of aviation and utility are p_A and p_U,[2]

[1]The average growth rate from 2005-2035 in EPPA-A is lower at 3.1%, as it includes the effects of the financial crisis of 2008-9, while the CAEP/8 forecasts were published in 2008 and could not have taken the demand shock into account. Therefore, the post-crisis growth from EPPA-A is used for this comparison.

[2]While the price of aviation relative to the price of utility in EPPA-A is not intended to be a universally applicable measure of real-world aviation price changes, using the price of utility as the numeraire for the relative price gives an expression of the change in price of aviation relative to all other goods. In the context of comparisons with revenue projections from APMT-E, this expression works particularly well, as price changes in APMT-E are driven by EPPA results for refined oil price increases. Refined oil prices passed to APMT-E are likewise normalized by the price of utility.

respectively, revenue in period t is given by:

$$R_t = \frac{p_{A,t}}{p_{U,t}} AT_t \tag{5.1}$$

Using the normalized price of aviation, Sectoral revenue in 2050 is \$672 Billion, and global aviation-sector revenue in 2050 is \$3.42 Trillion.

APMT-E is a detailed partial-equilibrium model of the global aviation sector. The model has been designed and built for the FAA Office of Environment and Energy by MVA consultancy in their continuing work in evaluating environmental policy (MVA, 2009). Because APMT-E is a partial equilibrium model, certain parameters must be determined exogenously. In order to correlate APMT-E's baseline results with those from EPPA-A, standard EPPA growth assumptions are used, including real GDP growth rate, and refined oil prices. APMT-E calculates consumer demand across each route group from these parameters and operational cost functions (taking into account the variety of available existing aircraft and new technologies). Additionally, APMT-E uses the same income elasticity of demand for aviation as EPPA-A. APMT-E calculates sector revenue based on the prices and demand for each route group.

In the APMT-E BAU case, U.S. demand (in revenue-ton kilometers, RTKs) grows at an average annual higher than the output growth rate in EPPA-A over the period from 2004-2050. EPPA-A also tracks industry revenue, which grows faster than output (as price increases over time) and more quickly than does revenue in APMT-E over the whole simulation period. If the post crisis rates are compared (2015-2050) growth rates are more aligned. These rates are summarized in Table 5.2.

The APMT-E Global BAU model predicts an average annual RTK growth rate of 4.1% from 2006 to 2050. The comparable EPPA-A growth rate is lower at 3.2%. The rate of revenue growth in APMT-E is 3.7%, also larger than the comparable EPPA-A rate of 3.4%. Complete global BAU trends are displayed in Figure 5-1, U.S. results are in Figure 5-2.

	Global			U.S.		
	2004-2050	2006-2050	2015-2050	2004-2050	2006-2050	2015-2050
EPPA-A						
Sector Output	3.2%	~	3.2%	2.6%	~	2.6%
Revenue	3.4%	~	3.7%	3.1%	~	3.2%
APMT-E						
RTK	~	4.1%	4.3%	~	2.6%	3.5%
Revenue	~	3.7%	4.0%	~	3.2%	3.0%

Table 5.2: EPPA-A and APMT-E growth rates

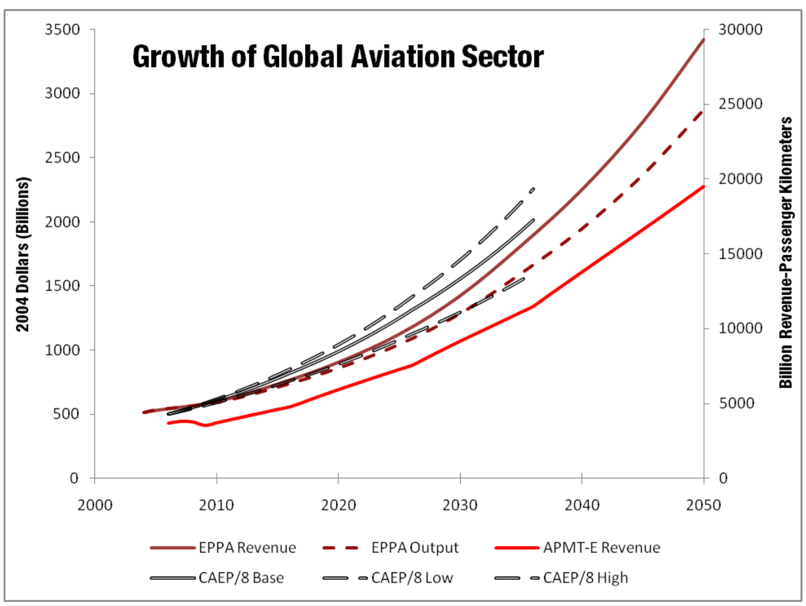

Figure 5-1: Baseline Results and CAEP/8 Forecasts

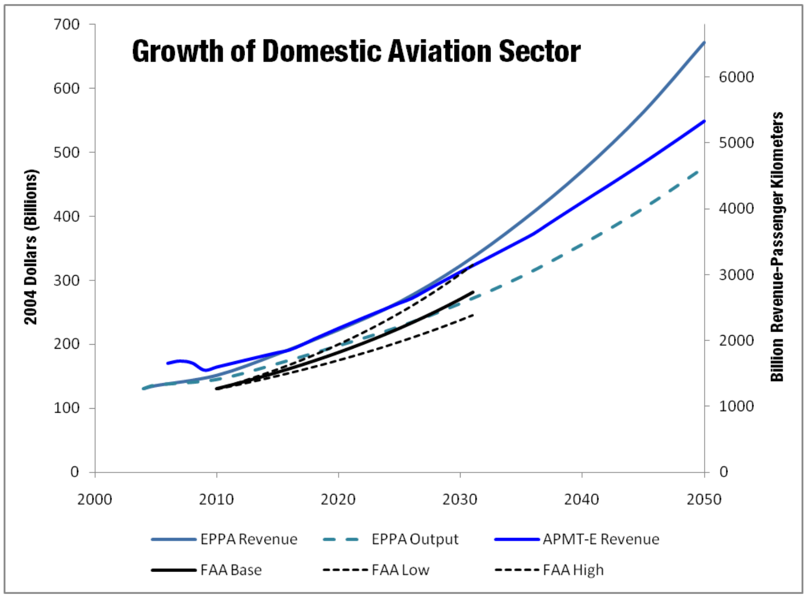

Figure 5-2: Baseline Results and FAA Forecasts

5.2 Global Emissions

5.2.1 BAU Emissions

While annex B regions constitute a majority of global emissions in the base year, due to slower growth combined by a quickly growing developing world they are projected to make up only 26% of global emissions by 2050. The global, annex B and U.S. GHG emissions of all Kyoto gases in CO2-equivalents are shown in Figure 5-3.

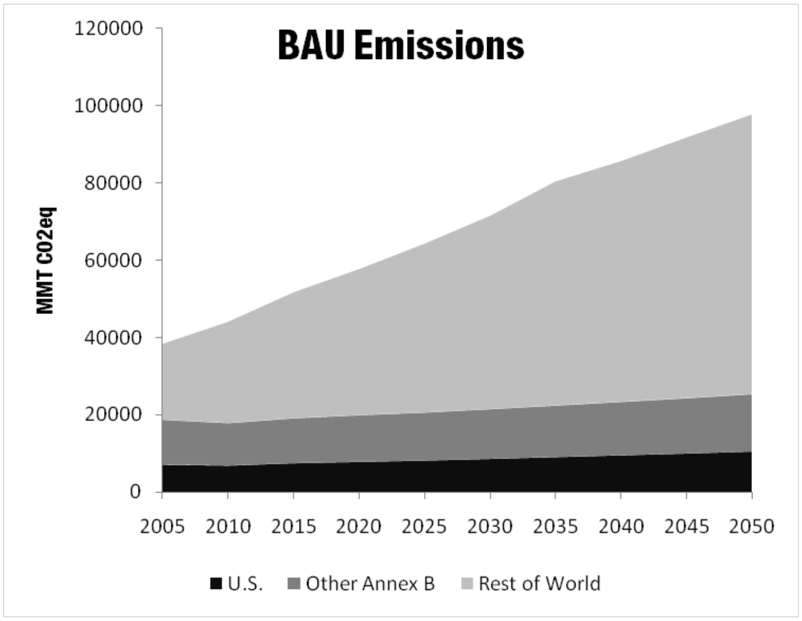

Figure 5-3: Global BAU Emissions

5.2.2 Policy-Constrained Emissions

By comparison, the POL case reduces emissions by 11.5% globally from the BAU case, and by 61.3% in annex B regions. In the U.S. the policy reduces emissions by 63.5% as compared to the no-policy case. Policy-scenario emissions are reported in Figure 5-4, and total change of U.S. and Global emissions compared to the baseline is shown in Table 5.3.

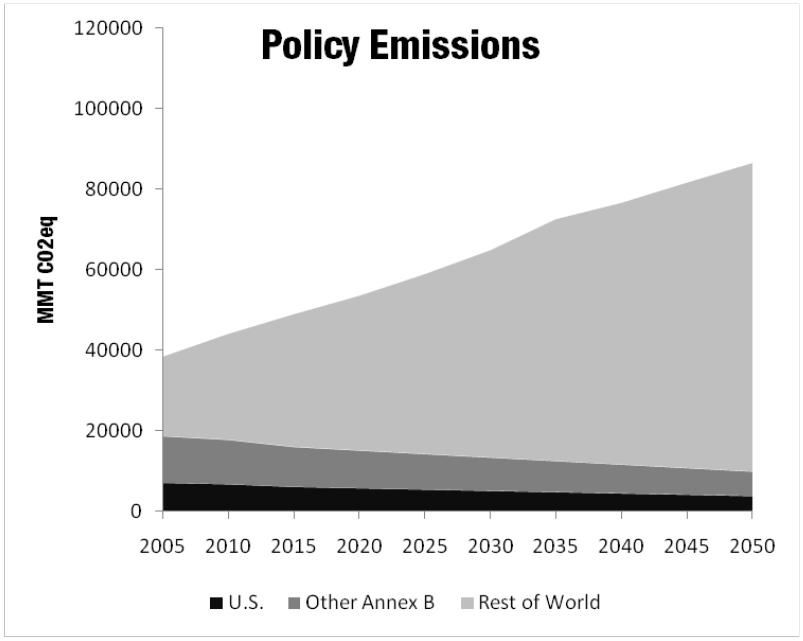

Figure 5-4: Global Emissions under Policy

	2004	2050	
		BAU	Policy
Global	36657	97837	86578
Annex B	18666	25306	9803
U.S.	7032	10417	3798

Table 5.3: Emissions in MMT CO2-eq

5.3 Price of Emissions

In the POL case, emissions permits are tradable across greenhouse gases according to their global warming potential, so the carbon price really reflects a CO2-equivalent price. The evolution of the carbon price shows the relative cost of carbon abatement across constrained regions. The price per ton of CO2-eq emitted in the U.S. rises from \$53.51 in 2020 to \$164.53 in 2050. Among the constrained regions this carbon prices are only lower in Russia, where the 2020 price of \$21.67 grows to \$107.53 in 2050. Near-term prices are higher than in the U.S. for most regions, but by 2050, Canada faces the highest carbon prices with \$327.38 per ton.

In addition to the economy-wide policy, a sectoral policy which caps aviation emissions at 2020 levels is applied. Two results are compared, one where trading between the aviation-sector cap and the rest of the economy is allowed, and one where trading is not. Both sectoral policy cases result in a separate carbon price for the aviation sector and for the rest of the economy. In the SECPOL_T case, where one-way permit purchases are allowed from the economy to the sector, the sectoral price is only ever as high as the economy wide price. The sectoral price may be lower than the economy-wide price, but if it goes above the economy-wide price, airlines will purchase permits from the rest of the economy. In the SECPOL_NT case, the aviation-sector is far more constrained for emissions reductions and sees a much higher price than the trading case, 28% higher than the trading case in 2050. Aviation price evolution is seen in Figure 5-5.

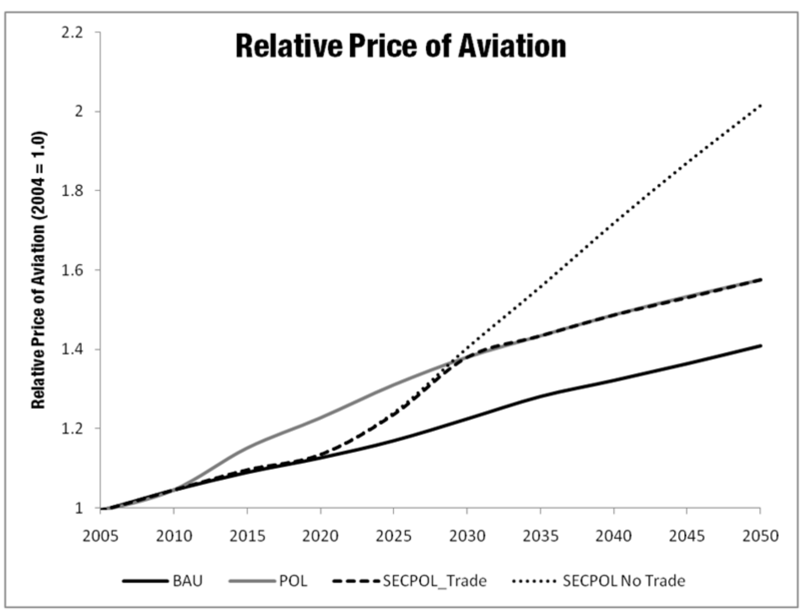

Figure 5-5: U.S. Relative Price of Aviation under Various Policies

5.4 Aviation Sector Emissions

When the POL case is applied across the economy, emissions reductions mostly come from non-aviation sectors of the economy. While economy-wide emissions are reduced 63.5% compared to the baseline in the U.S. in 2050, Aviation Sector emissions reductions are significantly less at only 19.5% compared to the baseline. Moreover, while total economy-wide emissions in the U.S. are decreasing at the end of the simulation at an average annual rate of 1.2% per year, aviation sector emissions are continuing to grow at a rate of 3.6% in both the POL and SECPOL_T cases. In the SECPOL_NT case, aviation emissions remain capped at 2020 levels throughout the simulation. Figure 5-6 shows U.S. aviation sector emissions in the baseline and various policy scenarios. Without viable alternative technologies, sectoral emissions continue to rise after a near-term period of relatively carbon-neutral growth (2010-2025).

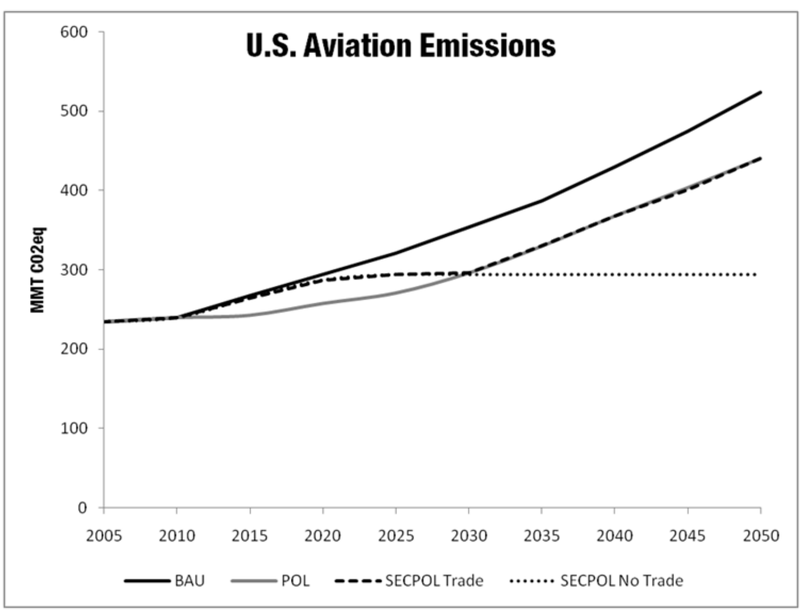

Figure 5-6: U.S. Aviation Emissions under Various Policies

5.5 Aviation Sector Output

Without backstop technologies or access to biofuels, the aviation sector experiences a significant price shock as the price of refined oil increases. Some adjustment to higher fuel prices is possible as production shifts away from fuel in the E-KL nest. This is evident over the period from the introduction of the policy (2010) until the rate of emissions growth meets that of the BAU scenario (2025). During this period, output continues to grow (average annual rate of 2.0%) while emissions do not (average annual rate of 0.8%). This endogenous effect reflects the potential for new, more efficient capital. After 2025, both BAU and POL scenario emissions grow at an average annual rate of 1.8%. The near-term (2010-2025) reduction in emissions is largely due to a combination of substitution away from fuel use in the cost function, and by reduction in output. After 2025, emissions reductions from BAU are due mainly to reduction in output, shown in Figure 5-7.

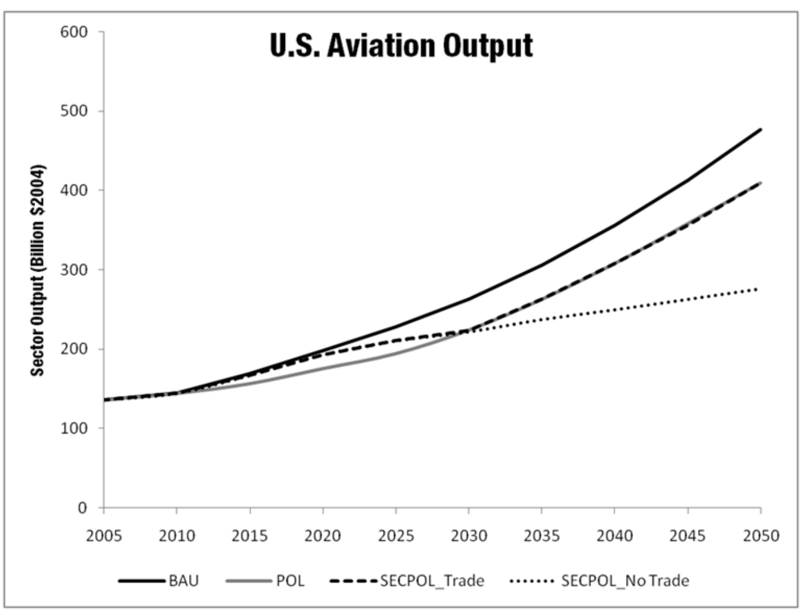

Figure 5-7: U.S. Aviation-Sector Output at 2004 Prices under Various Policies

5.6 Aviation Energy Efficiency

The average rate of efficiency growth in the aviation sector over in the BAU case is 1.275%. This rate is a composite of the autonomous energy efficiency improvement rate of 1% and an average annual rate of endogenous technical and management change of 0.275% per year. In the POL case and in the SECPOL_T case this average rate is identical and slightly higher than in the BAU at 1.32% per year, even though the periods when greater improvements are made are delayed by 10 years in the SECPOL_T case. In the SECPOL_NT case, despite a significant increase in carbon price compared to the SECPOL_T and POL cases, the average energy efficiency improvement rate is only 0.03% higher. The range of estimates is under the ATA goal of sustained 1.5% per year improvements, but is in the range of estimates made by Lee et al. (2001).

As the model demonstrates, while the goal of an increased energy efficiency improvement rate may be laudable, the costs must be taken in context of the preferences of the economy as a whole. The rate of energy efficiency improvement is highly sensitive to the elasticity of substitution between energy and the value-added nest, $\sigma_{E,KL}$. Because $\sigma_{E,KL}$ is very inelastic, then reductions in emissions in the aviation sector must be met by reduced output. But because demand for aviation is high, higher prices lead to emissions cuts elsewhere in the model, rather than reduced aviation emissions.

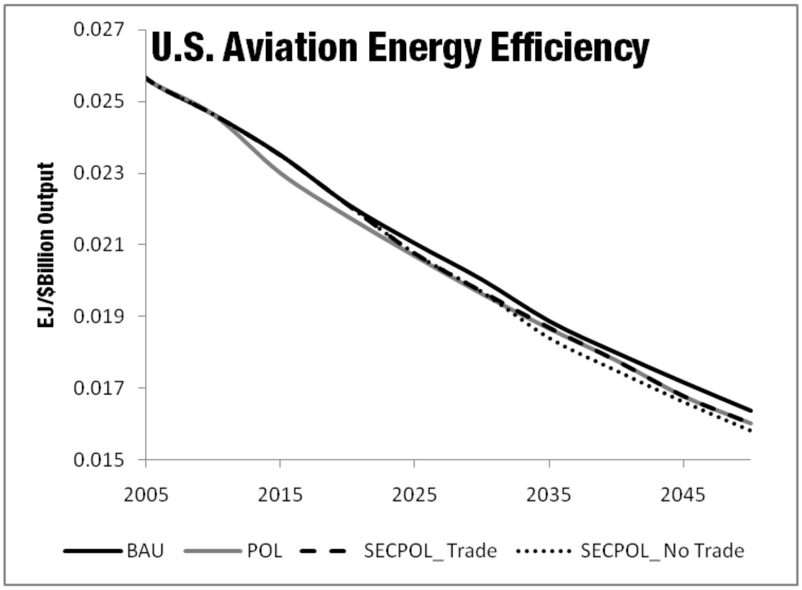

Figure 5-8: U.S. Aviation-Sectoral Energy Efficiency under Various Policies

5.7 Petroleum Use

This pattern is observable in the model-wide consumption of Refined Oil (ROIL). In the BAU scenario, scarce resources raise prices for ROIL across the board, but not sufficiently high for biofuels to completely displace ROIL use in any sector. By 2050, ROIL use is still increasing or holding steady in the largest-consuming sectors in the BAU case. This is not the case under the POL cap, wherein other sectors' ROIL use falls by 76% compared to the BAU case. Due to a lack of access to 'drop-in' biofuels, the aviation sector is the only sector whose refined oil use continues to grow through the model horizon. Figure 5-9 shows the response in the various cases.

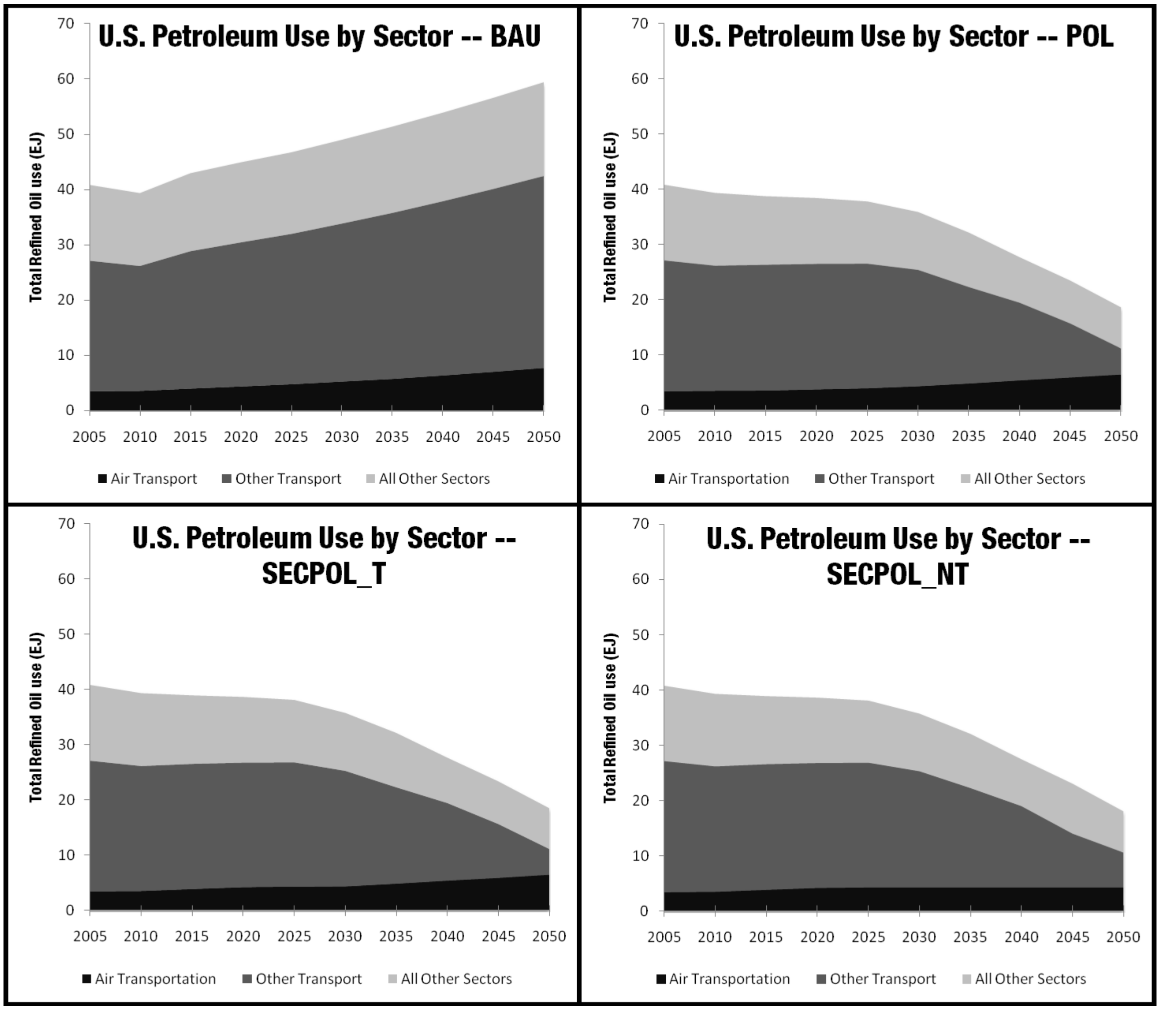

Figure 5-9: Refined Oil Use in the U.S. by Sector

5.8 Welfare Loss

While the welfare loss of the economy wide cap is significant-3.2% loss compared to BAU by 2050-the various aviation policies have limited effect on overall welfare gain or loss. Welfare is relatively insensitive to aviation policy optimality because of the limited size of the sector. In the U.S. as well as globally, both the SECPOL_T and SECPOL_NT cases are slightly less costly than the POL case in 2020. Table 5.4 shows the welfare change vs. BAU for each policy run. By 2050, however, the SECPOL_NT case is significantly more expensive in the U.S. than either of the policies that allow trading, which is to be expected. The sectoral cap restricts mitigation opportunities. Globally, the expected outcome would be similar, albeit proportionally smaller, as the economic inefficiencies in Annex B regions are a much smaller part of the global economy in 2050. But globally, the SECPOL_NT case results in a slight welfare improvement versus the POL case. Interestingly, this difference in welfare is due to a large shift in trade between constrained and unconstrained regions, a shift which also leads to an accompanying increase in global emissions. When imports of aviation are disabled, the POL case shows a slight welfare advantage over both the SECPOL_T and SECPOL_NT cases.

	U.S.		**Global**	
	2020	2050	2020	2050
Policy	-0.4248%	-3.1974%	-0.5167%	-2.9140%
Sectoral Policy, Trading	-0.4187%	-3.1854%	-0.5076%	-2.9120%
Sectoral Policy, No Trading	-0.4190%	-3.4396%	-0.5099%	-2.9128%

Table 5.4: Welfare Loss

5.9 International Trade

Interestingly, regions which see welfare gains from the sectoral cap without trade are those whose emissions under an economy-wide policy are not much larger than the 2020 cap, and who are in a position to engage in trade with regions with strong growth but firm caps. For example under the economy-wide cap, both Russia and the EU have slow growing aviation emissions, and therefore under the sectoral cap with no trading, they face lower sectoral carbon prices relative to the U.S. (35% and 60% lower, respectively). Thus, if European and Russian airlines can serve domestic markets in the U.S. while using domestic credits, their domestic economy exports more than they would in the economy-wide cap, and welfare loss from the policy decreases. Indeed, under the sectoral policy with no trade, imports of aviation are

77% higher in the U.S. than in the economy-wide policy.

5.10 Air Traffic Control Module

When the ATC module is enabled, the result is entirely dependent upon the parameter estimates chosen. The low-efficiency parameters result in minimal fuel efficiency gains at a substantial cost, while the high-efficiency parameters result in just the opposite. Table 5.5 shows the significant difference in outcomes based on the parameters assumed.

	Welfare Change		**Change in Fuel Intensity (EJ/$)**	
	BAU	POL	BAU	POL
High	0.752%	0.995%	-57.5%	-62.1%
Central	0.104%	0.248%	-23.8%	-25.1%
Low	-0.563%	-0.534%	-3.2%	-2.5%

Table 5.5: Advanced ATC: Changes in Energy Intensity and Welfare vs. No ATC

Except when the low parameter estimates are used, change in sectoral energy intensity is largely driven by ATC technology. In both the central and high parameter scenarios, model results conflict with reality. Given the assumption that BAU delay rates remain constant at 21% of flights, an energy intensity reduction of *greater* than 21% through delay mitigation seems unreasonable. Sectoral output and energy intensity are shown in Figure 5-10.

The addition of advanced ATC to the model has significant effects on sectoral emissions. While in the low parameter case, BAU emissions in 2050 are only 0.6% lower than without advanced ATC, in the central parameter case, they fall 1.5%. The high parameter case yields the unlikely result of a 3.3% drop in emissions. In the POL case, emissions levels remain the same, but the reduction in energy intensity leads to a drop in price (as production of aviation requires fewer emissions permits), and demand recovers more quickly.

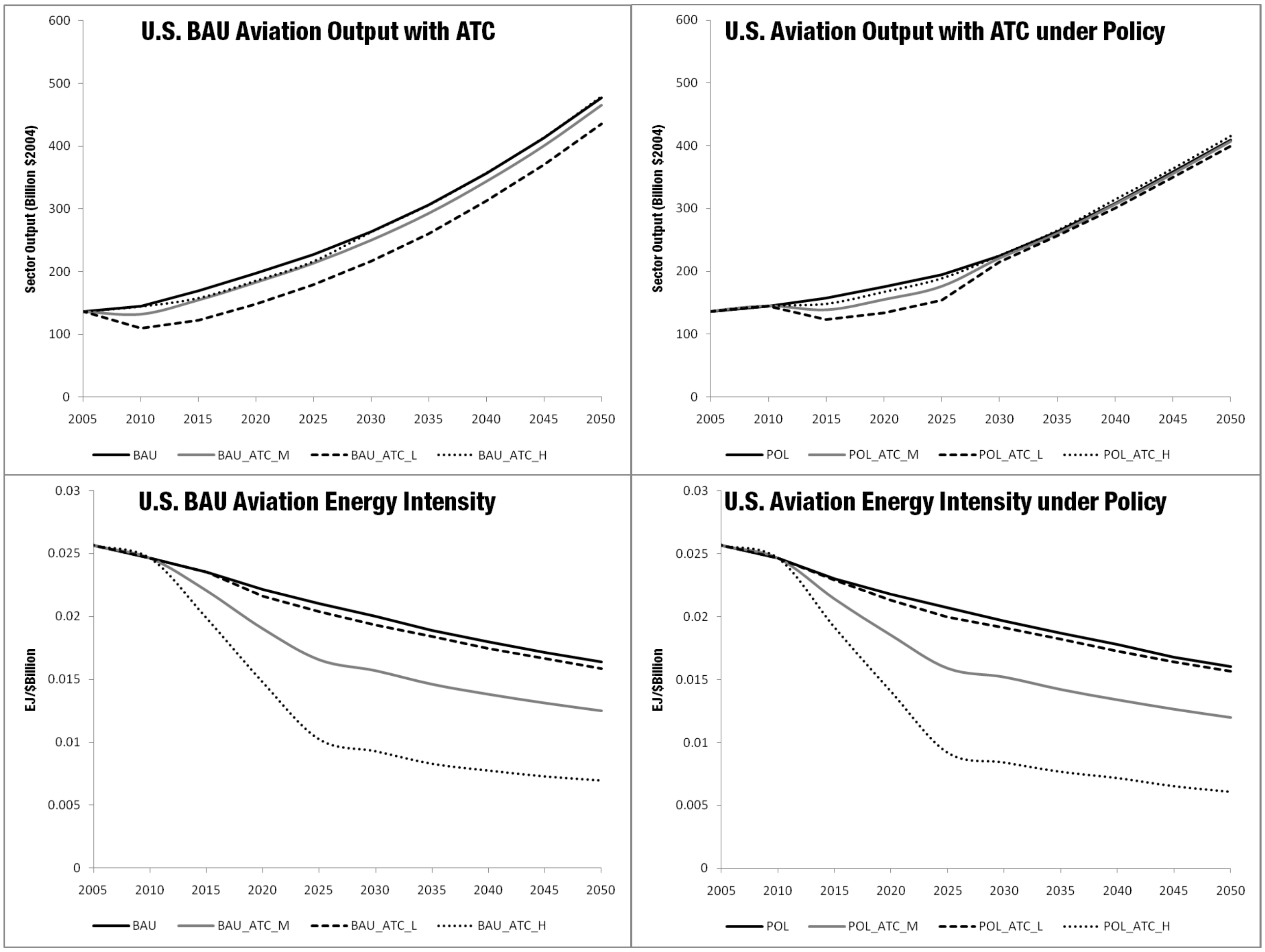

Figure 5-10: Advanced ATC Output and Energy Intensity

In both the BAU and POL scenarios, demand for air transport suffers in the near term when additional taxes are applied. Following the sunset of ATC taxes, however, air transport demand recovers much more quickly in the POL scenario.

5.11 Business Management Module

By explicitly allowing substitutability away from energy and toward the value-added nest in vintage production, the business management module reflects the ability of airlines to alter their schedules and operations to optimize energy efficiency with old capital. When applied, the module results in an increase in the average annual efficiency improvement rate from 1.275% to 1.32% in the BAU scenario. In the policy scenario, the increase provided by the business management module is relatively smaller as without it, the model has already pushed efficiency to a higher baseline. The module increases average annual efficiency improvement rates from 1.32% to 1.35%.

5.12 Model Sensitivity to Parameter Estimates

Changes in aviation sector output, both globally and in the U.S. are compared to the reference for each parameter's high and low state. The variations on each parameter are found in Table 3.8, while Figure 5-11 shows the model's sensitivity to each parameter.

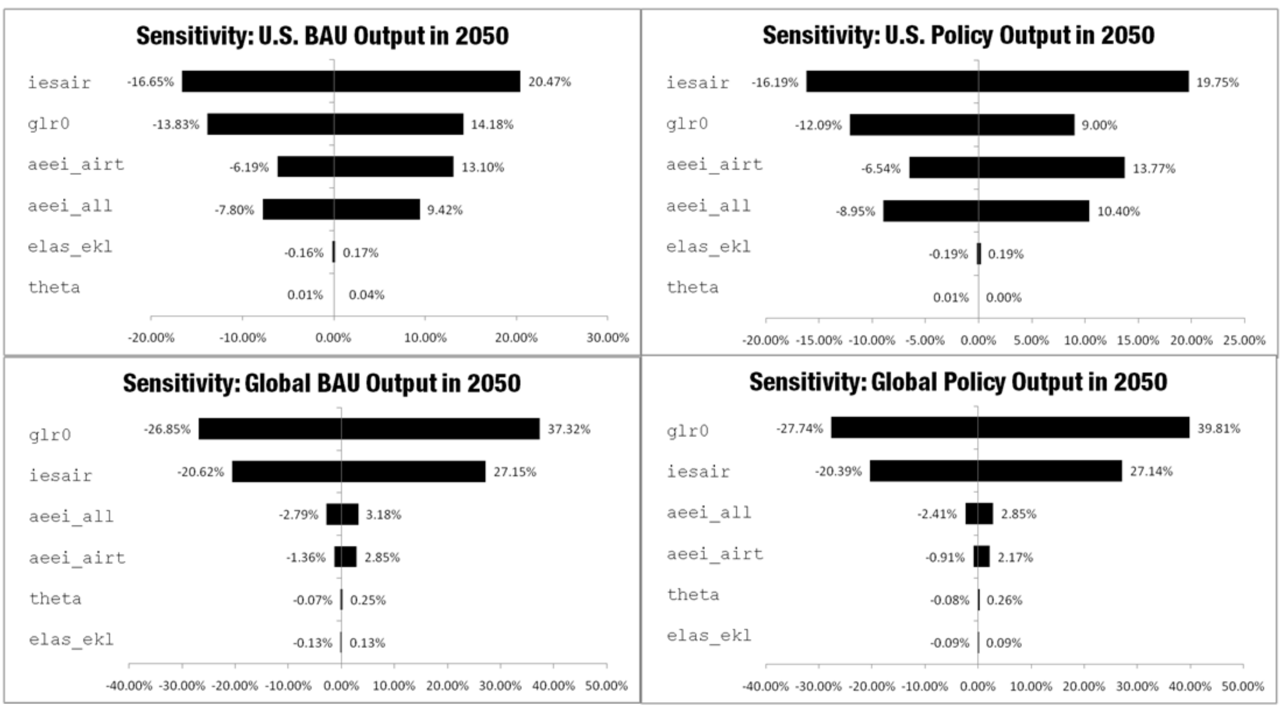

Figure 5-11: Variation in Model Output by Parameter

EPPA-A is highly sensitive to the income elasticity of demand for aviation, and to the exogenous labor productivity growth rate, neither of which are unexpected. Both parameters directly determine the period-on-period change in consumption. The relative sensitivity of the U.S. sectoral output compared to global output to the AEEI rate shows the degree to which the U.S. aviation sector is constrained by energy prices; elsewhere in the world, growth dominates. Perhaps most surprising is how inelastic the policy output is to changes in the elasticity of substitution between energy and the value-added nest. As this elasticity directly affects endogenous energy efficiency improvement rates, it would be expected to yield a higher variation in model output.

Chapter 6

Conclusions

While long-term results from EPPA-A are conditioned on an extended period of steady, positive economic growth around the world, the picture they paint is clear; To avoid the most serious impacts of climate change, wide-spread and large-scale emissions reductions are necessary. Compared to the present, the developing world will be the source of most future emissions, and must therefore be included in any future mitigation efforts. And while aviation technologies must be improved like all technologies, the policies which seek to improve technical performance must be understood in the context of their wider economic implications. Likewise, the problem of aviation sector emissions must be understood in the greater context of global emissions.

Aviation emissions constitute 1.8% of global GHG emissions in the base-year of 2004. By 2050 in the BAU model, this has increased to only 2.3%, meaning that while aviation's share of emissions is growing, non-aviation emissions are still growing rapidly as well. Even in the policy cases where total emissions in annex B regions are halved while aviation emissions in the same regions increase, aviation's share of global emissions rises to only 2.6%—largely due to the developing world's rapid growth. Among annex B regions, however, the share of aviation emissions in policy constrained regions more than triples from 2.6% in 2004 to 8.0% in 2050, and from 3.3% in 2004 to 11.6% in 2050 in the U.S. Due to the relatively quick growth of developing-world emissions, the significant reductions in the U.S. and other annex

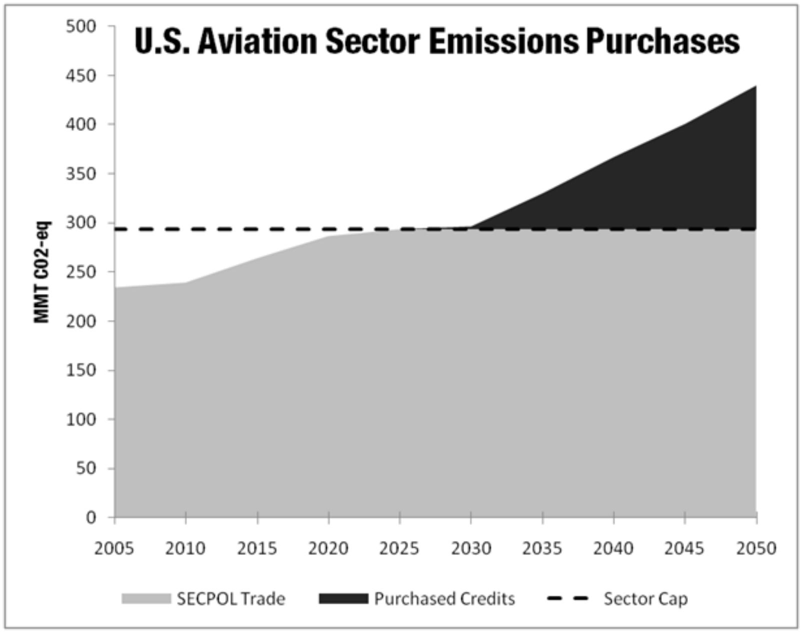

Figure 6-1: Under the Sectoral Policy, Trading is Efficient, Unless Allocations are Free

B regions have little impact on the primary policy goal of reduced global emissions. Thus further reductions in aviation emissions in annex B countries are among the most expensive and difficult emissions reductions available in 2050.

The IATA and ATA's commitments to sector-wide carbon mitigation are laudable, but are, quite understandably, too focused on aviation. From a welfare perspective, the difference between a sectoral policy and an economy-wide policy is negligible as long as trading is available. Between these policies, sectoral output and the price of aviation are equivalent in 2050, with the only difference occurring during the near-term (2010-2020) when aviation emissions are not capped in the sectoral policy. However, a separate aviation-only cap can have large distributive effects if permit allocations are free. The cap proposed by the IATA will leave the sector short in every scenario. In the sectoral cap with trading, the U.S. aviation sector will need to purchase 33.3% of their permits from the economy-wide cap by 2050. If allocations are free, this sectoral distribution will leave the sector significantly under-allocated, and the cost of transfers will significantly increase the price of the policy.

The effects of trade on global welfare and emissions can be large. The IATA's goal of avoiding an uncompetitive patchwork of policies may be unachievable. If the trend toward an international system of coordinated national policies continues along with airspace liberalization and international access to domestic markets, the differing systems of border adjustments will become even more important. The ETS's current system will require airlines to purchase permits for half the emissions of extra-European flights that originate or arrive in Europe. If an upstream policy like H.R. 2454 (which includes airport bunker fuels) becomes law in the U.S., transatlantic flights that buy fuel in the U.S. and fly to Europe will face double counting of emissions. But aviation, unlike energy intensive manufacturing, is relatively easily integrated into a system of border adjustments.

The efficacy of air traffic control improvements faces serious uncertainty. Without a clear program plan, the costs and potential savings of future technologies are speculative. However, given the range of estimates used in the EPPA-A ATC module, it is clear that as long as ATC improvements are funded through additional passenger taxes, sectoral output will decrease compared to baseline. However the decline in sector output is matched by significantly lower fuel intensity.

Air Traffic Control improvements are not a market-based decision; rather, they are exogenously determined by public policy. In EPPA-A, tax rates for advanced ATC are set to meet expected government expenditures on ATC infrastructure. A more efficient solution would be a usage fee for ATC infrastructure charged to airlines. While the fee would still be the result of a policy determination, airlines would have an interest in the rate being set to keep pace with traffic growth, and to achieve whatever efficiency gains maximize profits based on the policy and fuel-price constraints they face.

Biofuels play a large role in reducing fuel consumption in EPPA-A, but are disallowed from use in the aviation sector. By 2050, U.S. biofuel consumption is greater than refined oil consumption in all non-aviation sectors. Reductions in refined oil demand due to reduction in output and energy efficiency savings are even larger, constituting more than half of total reductions. But reductions in aviation fuel use are hard to come by; refined oil use by the aviation sector is only 18% lower in the policy scenario than in the BAU case. More importantly, there are significant reductions still available from the portion of the household transportation sector which has not switched to biofuels. Figure 6-2 shows the sectoral breakdown of refined oil use changes in the policy scenario. At the model horizon, the marginal cost of biofuels is still 14% higher than refined oil for aviation in the U.S., so while at some point in the future aviation will need to switch to biofuels, it is likely the last sector which will do so. This is not the case in all policy constrained regions; if biofuels with the same incremental cost as cellulosic ethanol were available for aviation use, they would enter into use in the Japanese aviation sector in 2030, and the European sector in 2045.

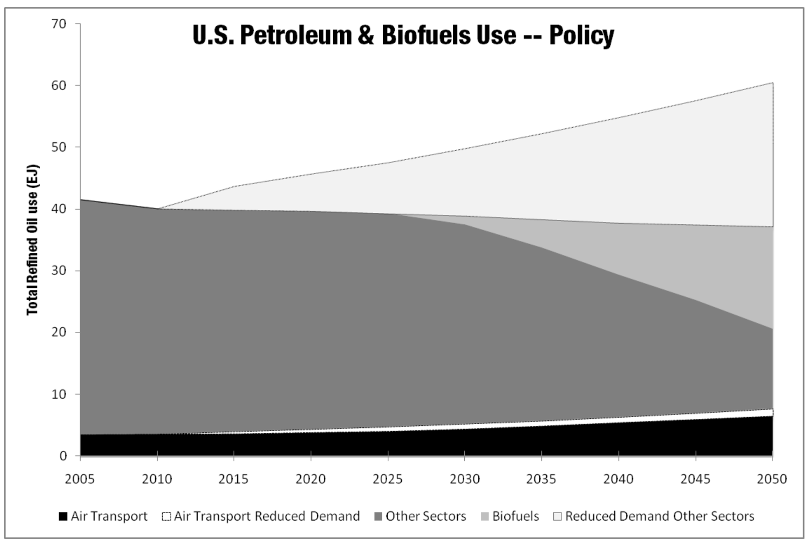

Figure 6-2: Reductions are available in most other Sectors, but aviation reductions are sparse

The aviation sector is key to economic expansion, but while its economic footprint is large, relative to economy, its emissions are not. In the future, aviation emissions will eventually need to be reduced, but both policy measures and investments in research and infrastructure should achieve the cheapest reductions first. Given the unlikelihood of a global sectoral aviation cap, there is no compelling reason why the aviation sector should have an independent goal of carbon neutral growth after 2020, especially if it takes place apart from an economy-wide cap. Aviation's inclusion in the economy-wide cap offers the best chance for fair allocations of free permits and for efficient reductions of emissions across sectors, but it is essential that aviation-specific border adjustments fairly account for emissions permits or taxes purchased or paid in other regions.

Appendix A

Matrix Balancing Code

```
*this program rebalances the EPPA5 social accounting matrix.

$title  Read the Social Accouting Matrix and Balance

*These are necessary EPPA Sets to perform the balance

SET     I  SECTORS /
  CROP  Agriculture - crops
  LIVE  Agriculture - livestock
  FORS  Agriculture - forestry
  FOOD  Food products
  COAL  Coal
  OIL Crude Oil
  ROIL  Refined Oil
  GAS Gas
  ELEC  Electricity
  EINT  Energy-intensive Industries
  OTHR  Other Industries
  SERV  Services
  TRAN  Transport
  AIRT    Air Transport
  CGD Savings Good/;

SET     R   REGIONS /
  USA United States
  CAN Canada
  MEX Mexico
  JPN Japan
  ANZ Australia - New Zealand
  EUR Europe
  ROE Eastern Europe
  RUS Russia Plus
  ASI East Asia
  CHN China
  IND India
  BRA Brazil
  AFR Africa
  MES Middle East
  LAM Latin America
  REA Rest of Asia /;

*llk and llkf are not real eppa sets, but are useful here
SET LLK/
  LAB
```

```
  LND
  CAP/;

SET LLKF/
  LAB
  LND
  CAP
  FIX/;

SET E/
  COAL
  OIL
  ROIL
  GAS
  ELEC/;

SET OIL/
  OIL/;

alias  (i,g);
alias (r,rr);

*include the data set you wish to modify:
$include airdat.dat

*include energy adjustments
$include adjustments.dat

*create flag to initialize energy adjustments or not
parameter adj;
adj = 1;

*make adjustments
xp0("usa","airt") = xp0("usa","airt") + xp0_adjustments;
xdc0("usa","airt") = xdc0("usa","airt") + xdc0_adjustments;
xdp0(r,i,g) = xdp0(r,i,g) + xdp0_adjustments(r,i,g);
display 'zombie';
display xp0, xdc0, xdp0;

eind("roil","airt",r)$adj = eind_airt_adjustments(r);
eind("roil","tran",r)$adj = eind("roil","tran",r) + eind_tran_adjustments(r);
efd("roil",r)$adj = efd("roil",r) + efd_adjustments(r);

*Because we want to use the Least Squares method of solvers, negatives pose a problem.
*The 'absolute value' function in gams is discontinuous, and none of the NLP solvers let
    you use it
*For this reason, split any parameters with values <0 into a positive and negative
    parameter.
*The positive parameters are added in the functions, and the negatives are subtracted.
parameters posptxy0, negptxy0;
posptxy0(r,g)$(ptxy0(r,g) ge 0) = ptxy0(r,g);
negptxy0(r,g)$(ptxy0(r,g) le 0) = ptxy0(r,g)*(-1);
parameters possavf0, negsavf0;
possavf0(r)$(savf0(r) ge 0) = savf0(r);
negsavf0(r)$(savf0(r) le 0) = savf0(r)*(-1);
parameters postrg0, negtrg0;
postrg0(r)$(trg0(r) ge 0) = trg0(r);
negtrg0(r)$(trg0(r) le 0) = trg0(r)*(-1);
parameters td, postd, negtd;
postd(r,g) = posptxy0(r,g)/xp0(r,g);
negtd(r,g) = negptxy0(r,g)/xp0(r,g);

* Balance the SAM using least squares
*declare variables for use in optimization
variable  obj Objective -- least squares deviation;

positive
variable        est_xp0(r,g)    Estimate of production
```

```
    est_xdp0(r,i,g)   Estimate of domestic intermediate usage
    est_xmp0(r,i,g)   Intermediate demand for imports
    est_xdc0(r,g)   Estimate of domestic hhold demand
    est_xmc0(r,g)   Estimate of imports for hhold cons
    est_xdg0(r,g)   Estimate of government domestic demand
    est_xmg0(r,g)   Estimate of government import demand
    est_xdi0(r,g)   Estimate of investment demand
    est_vst(g,r)    Estimate of exports of transportation
    est_es0(r,g)    Estimate of exports
    est_wtflow0(r,rr,g) Estimate of world trade flows
    est_xm0(r,g)    Estimate of imports
    est_tx(g,rr,r)    Estimate of export tax (fixed)
    est_vtwr(i,g,rr,r)  Estimate of trade margins
    est_tm(g,rr,r)    Estimate of import tariff (fixed)
    est_cons0(r)    Estimate of total hhold consumption
    est_pc0(g,r)    Estimate of price level (fixed)
    est_kapd0(r,g)    Intermediate demand for Kapital
    est_labd0(r,g)    Intermediate demand for Labor
    est_ffactd0(r,g)  Intermediate demand for Land
    est_posptxy0(r,g) Positive sectoral sum of excise tax (check these)?
    est_negptxy0(r,g) Negative sum of excise tax
    est_taxh0(r)    Total tax revenue
    est_savh0(r)    Hhold savings?
    est_tf(llk,g,r)   Tax rate on fixed factors (fixed)
    est_ti(i,g,r)   Tax rate on intermediates (fixed)
    est_possavf0(r)   Positive foreign savings (capital flows into region r)
    est_negsavf0(r)   Negative foreign savings (capital flows out of region r)
    est_pg0(g,r)    Government price level (fixed)
    est_postrg0(r)    Positive tax on government purchases
    est_negtrg0(r)    Negative tax on government purchases (check these)

*declare equations which will be passed to the solver
equations       lsqobj          Defines norm of the deviation with a least squares
    objective
                firm_sales_balance(r,g)      firm income
    firm_cost_balance(r,g)       firm expenditures
    export_balance(r,g) export balance
    import_balance(r,g) import balance
    hhold_consumption_balance(r)  Household Consumption Balance
    hhold_gov_income_balance(r) Household Income Balance
    oilbal(oil)   Oil Balance
    foreign_ex_balance(r) Foreign Exchange Balance
    savings_balance(r)  Savings Balance
    regional_balance(r) Regional Balance
    trade_balance   Trade Balance
    import_balance_cif(r,g);  Import Balance (cost, insurance, freight)

*obj is the sum of square difference between a variable and it's starting point: we try to
     minimize this
lsqobj..        obj =e=  5 * sum((r,i,g)$xdp0(r,i,g), xdp0(r,i,g) * sqr(est_xdp0(r,i,g)/
    xdp0(r,i,g)-1))
      + sum((r,i,g)$xp0(r,g), xp0(r,g) * sqr(est_xp0(r,g)/xp0(r,g)-1))
      + sum((r,g)$es0(r,g), es0(r,g) * sqr(est_es0(r,g)/es0(r,g)-1))
      + sum((r,i,g)$xmp0(r,i,g), xmp0(r,i,g) * sqr(est_xmp0(r,i,g)/xmp0(r,i,g)-1))
      + sum((r,g)$kapd0(r,g), kapd0(r,g) * sqr(est_kapd0(r,g)/kapd0(r,g)-1))
      + sum((r,g)$labd0(r,g), labd0(r,g) * sqr(est_labd0(r,g)/labd0(r,g)-1))
      + sum((r,g)$ffactd0(r,g), ffactd0(r,g) * sqr(est_ffactd0(r,g)/ffactd0(r,g)-1))
      + sum((r,g)$posptxy0(r,g), posptxy0(r,g) * sqr(est_posptxy0(r,g)/posptxy0(r,g)-1))
      + sum((r,g)$negptxy0(r,g), negptxy0(r,g) * sqr(est_negptxy0(r,g)/negptxy0(r,g)-1))
      + sum((r,g)$xdc0(r,g), xdc0(r,g) * sqr(est_xdc0(r,g)/xdc0(r,g)-1))
      + sum((r,g)$xmc0(r,g), xmc0(r,g) * sqr(est_xmc0(r,g)/xmc0(r,g)-1))
      + sum((r,g)$xdg0(r,g), xdg0(r,g) * sqr(est_xdg0(r,g)/xdg0(r,g)-1))
      + sum((r,g)$xmg0(r,g), xmg0(r,g) * sqr(est_xmg0(r,g)/xmg0(r,g)-1))
      + sum((r,g)$xdi0(r,g), xdi0(r,g) * sqr(est_xdi0(r,g)/xdi0(r,g)-1))
      + sum((g,r)$vst(g,r), vst(g,r) * sqr(est_vst(g,r)/vst(g,r)-1))
      + sum((rr,r,g)$wtflow0(rr,r,g), wtflow0(rr,r,g) * sqr(est_wtflow0(rr,r,g)/wtflow0(rr
          ,r,g)-1))
      + sum((r,g)$xm0(r,g), xm0(r,g) * sqr(est_xm0(r,g)/xm0(r,g)-1))
```

```
      + sum((g,rr,r)$tx(g,rr,r), tx(g,rr,r) * sqr(est_tx(g,rr,r)/tx(g,rr,r)-1))
      + sum((i,g,rr,r)$vtwr(i,g,rr,r), vtwr(i,g,rr,r) * sqr(est_vtwr(i,g,rr,r)/vtwr(i,g,rr
          ,r)-1))
      + sum((g,rr,r)$tm(g,rr,r), tm(g,rr,r) * sqr(est_tm(g,rr,r)/tm(g,rr,r)-1))
      + sum((r)$cons0(r), cons0(r) * sqr(est_cons0(r)/cons0(r)-1))
      + sum((r,g)$pc0(g,r), pc0(g,r) * sqr(est_pc0(g,r)/pc0(g,r)-1))
      + sum((r,g)$taxh0(r), taxh0(r) * sqr(est_taxh0(r)/taxh0(r)-1))
      + sum((r,g)$possavf0(r), possavf0(r) * sqr(est_possavf0(r)/possavf0(r)-1))
      + sum((r,g)$negsavf0(r), negsavf0(r) * sqr(est_negsavf0(r)/negsavf0(r)-1))
      + sum((r,g)$postrg0(r), postrg0(r) * sqr(est_postrg0(r)/postrg0(r)-1))
      + sum((r,g)$negtrg0(r), negtrg0(r) * sqr(est_negtrg0(r)/negtrg0(r)-1))
      + sum((r)$savh0(r), savh0(r) * sqr(est_savh0(r)/savh0(r)-1));

*these are the SAM balancing criteria:
firm_sales_balance(r,g)..    est_xp0(r,g) =e= sum(i, est_xdp0(r,g,i)) + est_xdc0(r,g)
          + est_xdg0(r,g) + est_xdi0(r,g) + est_vst(g,r) + est_es0(r,g);
firm_cost_balance(r,g)..  est_xp0(r,g) =e= sum(i, (est_xdp0(r,i,g)+ est_xmp0(r,i,g))*(1+
    est_ti(i,g,r)))
          + est_kapd0(r,g)*(1+est_tf("cap",g,r)) + est_labd0(r,g)*(1+est_tf("lab",g,r))
          + est_ffactd0(r,g)*(1+est_tf("lnd",g,r)) + est_posptxy0(r,g) - est_negptxy0(r,g)
               ;
export_balance(r,g)..   est_es0(r,g) =e= sum(rr,est_wtflow0(rr,r,g));
import_balance(r,g)..   est_xm0(r,g) =e= sum(rr,(est_wtflow0(r,rr,g)*(1+est_tx(g,rr,r)) +
    sum(i,est_vtwr(i,g,rr,r)))*(1+est_tm(g,rr,r)));
hhold_consumption_balance(r)..  est_cons0(r) =e= sum(g,(est_xmc0(r,g)+est_xdc0(r,g))*
    est_pc0(g,r));
hhold_gov_income_balance(r).. est_cons0(r) + sum(g,(est_xdg0(r,g)+est_xmg0(r,g))*est_pg0(g
    ,r)) + sum(g,est_xdi0(r,g)) =e=
            sum(g,est_labd0(r,g)) + sum(g,est_kapd0(r,g)) + sum(g,est_ffactd0(r,g))
            + est_taxh0(r) + est_possavf0(r) - est_negsavf0(r);
oilbal(oil).. sum(R, est_XP0(R,"oil")) =e= sum(r,SUM(g,est_XDP0(R,"OIL",g)) + est_XDC0(R,"
    OIL") + est_XDG0(R,"OIL") + est_XDI0(R,"OIL")
            + est_ES0(R,"OIL"));
foreign_ex_balance(r).. sum((g,rr), est_wtflow0(rr,r,g)*(1+est_tx(g,r,rr)))+ sum(g,
    est_vst(g,r)) + est_possavf0(r) - est_negsavf0(r) =e=
            sum((g,rr),(est_wtflow0(r,rr,g)*(1+est_tx(g,rr,r)) + sum(i,est_vtwr(i,g,rr,r))
                ));
savings_balance(r).. est_savh0(R) + est_possavf0(r) - est_negsavf0(r) =e= sum(g,est_xdi0(r
    ,g));
regional_balance(r).. sum(g, est_labd0(r,g)+est_kapd0(r,g)+est_ffactd0(r,g)) +
    est_possavf0(r) - est_negsavf0(r) + est_taxh0(r) =e=
        sum(g,est_xdg0(r,g)+est_xmg0(r,g)) + est_postrg0(r) - est_negtrg0(r) + sum(g,
            est_xdi0(r,g)) + est_cons0(r);
trade_balance..   sum((i,r), est_vst(i,r)) =e= sum((i,g,rr,r), est_vtwr(i,g,rr,r));
import_balance_cif(r,g).. est_xm0(r,g) =e= sum(i,est_xmp0(r,g,i)) + est_xmc0(r,g) +
    est_xmg0(r,g);


*set variable levels to initial values
est_xp0.l(r,g) = xp0(r,g);
est_xdp0.l(r,i,g) = xdp0(r,i,g);
est_xdc0.l(r,g) = xdc0(r,g);
est_xdg0.l(r,g) = xdg0(r,g);
est_xmg0.l(r,g) = xmg0(r,g);
est_xdi0.l(r,g) = xdi0(r,g);
est_vst.l(g,r) = vst(g,r);
est_es0.l(r,g) = es0(r,g);
est_wtflow0.l(r,rr,g) = wtflow0(r,rr,g);
est_xm0.l(r,g) = xm0(r,g);
est_vtwr.l(i,g,rr,r) = vtwr(i,g,rr,r);
est_cons0.l(r) = cons0(r);
est_xmc0.l(r,g) = xmc0(r,g);
est_xmp0.l(r,i,g) = xmp0(r,i,g);
est_kapd0.l(r,g) = kapd0(r,g);
est_labd0.l(r,g) = labd0(r,g);
est_ffactd0.l(r,g) = ffactd0(r,g);
est_posptxy0.l(r,g) = posptxy0(r,g);
est_negptxy0.l(r,g) = negptxy0(r,g);
```

```
est_possavf0.l(r) = possavf0(r);
est_negsavf0.l(r) = negsavf0(r);
est_postrg0.l(r) = postrg0(r);
est_negtrg0.l(r) = negtrg0(r);
est_taxh0.l(r) = taxh0(r);
est_savh0.l(r) = savh0(r);
*est_postd.l(r,g) = postd(r,g);
*est_negtd.l(r,g) = negtd(r,g);

*prices and tax rates are fixed
est_pg0.fx(g,r) = pg0(g,r);
est_tx.fx(g,rr,r) = tx(g,rr,r);
est_pc0.fx(g,r) = pc0(g,r);
est_tm.fx(g,rr,r) = tm(g,rr,r);
est_tf.fx(llk,g,r) = tf(llk,g,r);
est_ti.fx(i,g,r) = ti(i,g,r);

*fix all variables which were originally at zero to zero
est_xp0.fx(r,g)$(xp0(r,g) = 0) = 0;
est_xdp0.fx(r,i,g)$(xdp0(r,i,g) = 0) = 0;
est_xdc0.fx(r,g)$(xdc0(r,g) = 0) = 0;
est_xdg0.fx(r,g)$(xdg0(r,g) = 0) = 0;
est_xmg0.fx(r,g)$(xdg0(r,g) = 0) = 0;
est_xdi0.fx(r,g)$(xdi0(r,g) = 0) = 0;
est_vst.fx(g,r)$(vst(g,r) = 0) = 0;
est_es0.fx(r,g)$(es0(r,g) = 0) = 0;
est_wtflow0.fx(r,rr,g)$(wtflow0(r,rr,g) = 0) = 0;
est_xm0.fx(r,g)$(xm0(r,g) = 0) = 0;
est_tx.fx(g,rr,r)$(tx(g,rr,r) = 0) = 0;
est_vtwr.fx(i,g,rr,r)$(vtwr(i,g,rr,r) = 0) = 0;
est_tm.fx(g,rr,r)$(tm(g,rr,r) = 0) = 0;
est_tf.fx(llk,g,r)$(tf(llk,g,r) = 0) = 0;
est_ti.fx(i,g,r)$(ti(i,g,r) = 0) = 0;
est_pg0.fx(g,r)$(pg0(g,r) = 0) = 0;
est_pc0.fx(g,r)$(pc0(g,r) = 0) = 0;
est_cons0.fx(r)$(cons0(r) = 0) = 0;
est_xmc0.fx(r,g)$(xmc0(r,g) = 0) = 0;
est_xmp0.fx(r,i,g)$(xmp0(r,i,g) = 0) = 0;
est_kapd0.fx(r,g)$(kapd0(r,g) = 0) = 0;
est_labd0.fx(r,g)$(labd0(r,g) = 0) = 0;
est_ffactd0.fx(r,g)$(ffactd0(r,g) = 0) = 0;
est_posptxy0.fx(r,g)$(posptxy0(r,g) = 0) = 0;
est_negptxy0.fx(r,g)$(negptxy0(r,g) = 0) = 0;
est_possavf0.fx(r)$(possavf0(r) = 0) = 0;
est_negsavf0.fx(r)$(negsavf0(r) = 0) = 0;
est_postrg0.fx(r)$(postrg0(r) = 0) = 0;
est_negtrg0.fx(r)$(negtrg0(r) = 0) = 0;
est_taxh0.fx(r)$(taxh0(r) = 0) = 0;
est_savh0.fx(r)$(savh0(r) = 0) = 0;
*est_postd.fx(r,g)$(postd(r,g) = 0) = 0;
*est_negtd.fx(r,g)$(negtd(r,g) = 0) = 0;

*pass the equations to the model
model lsqr/
  lsqobj
  firm_sales_balance
  firm_cost_balance
  hhold_consumption_balance
  hhold_gov_income_balance
  export_balance
  import_balance
  oilbal
  foreign_ex_balance
  savings_balance
  regional_balance
  trade_balance
  import_balance_cif/;
```

```
*solve!!!
option NLP=pathnlp;
solve lsqr using NLP minimizing obj;

*put everything back into its original parameter
xp0(r,g) = est_xp0.l(r,g);
xdp0(r,i,g) = est_xdp0.l(r,i,g);
xdc0(r,g) = est_xdc0.l(r,g);
xdg0(r,g) = est_xdg0.l(r,g);
xmg0(r,g) = est_xmg0.l(r,g);
xdi0(r,g) = est_xdi0.l(r,g);
vst(g,r) = est_vst.l(g,r);
es0(r,g) = est_es0.l(r,g);
wtflow0(r,rr,g) = est_wtflow0.l(r,rr,g);
xm0(r,g) = est_xm0.l(r,g);
vtwr(i,g,rr,r) = est_vtwr.l(i,g,rr,r);
cons0(r) = est_cons0.l(r);
xmc0(r,g) = est_xmc0.l(r,g);
xmp0(r,i,g) = est_xmp0.l(r,i,g);
kapd0(r,g) = est_kapd0.l(r,g);
labd0(r,g) = est_labd0.l(r,g);
ffactd0(r,g) = est_ffactd0.l(r,g);
ptxy0(r,g) = est_posptxy0.l(r,g) - est_negptxy0.l(r,g);
savf0(r) = est_possavf0.l(r) - est_negsavf0.l(r);
trg0(r) = est_postrg0.l(r) - est_negtrg0.l(r);
taxh0(r) = est_taxh0.l(r);
savh0(r) = est_savh0.l(r);
pg0(g,r) = est_pg0.l(g,r);
tx(g,rr,r) = est_tx.l(g,rr,r);
pc0(g,r) = est_pc0.l(g,r);
tm(g,rr,r) = est_tm.l(g,rr,r);
tf(llk,g,r) = est_tf.l(llk,g,r);
ti(i,g,r) = est_ti.l(i,g,r);

*initialize the put file
file balance /balance.dat/;

*For brevity's sake, the reporting has been redacted, but uses the
*same method as eppaput.gms

execute_unload "all.gdx"
```

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