The Impact of Climate Policy on US Aviation*

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*Reprinted from
Journal of Transport Economics and Policy, 47(1):1–15

Reprint 2013-1

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Journal of Transport Economics and Policy, Volume 47, Part 1, January 2013, pp. 1–15

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The authors would like to thank Thomas Cuddy, Maryalice Locke, Richard Hancox, Caroline Sinclair, Carl Tipton, and Daniel Rankin for valuable input. Any errors are the sole responsibility of the authors. The authors also acknowledge financial support from the Federal Aviation Administration and the Erich-Becker Foundation (Wollersheim). The Joint Program on the Science and Policy of Global Change is funded by the US Department of Energy and a consortium of government and industrial sponsors (for a complete list, see http://globalchange.mit.edu/sponsors/current.html). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the organisations listed above. Any errors are the sole responsibility of the authors.

Abstract

We use an economy-wide model to estimate the impact of a representative climate policy on fuel prices and economic activity, and a partial equilibrium model of the aviation industry to estimate changes in aviation carbon dioxide emissions and operations. Between 2012 and 2050, with reference demand growth benchmarked to ICAO/GIACC (2009) forecasts, we find that aviation emissions increase by 130 per cent. In our policy scenarios, emissions increase by between 103 per cent and 123 per cent. Under the assumptions in our analysis, aviation contributes to climate policy targets by funding emissions reductions in sectors with less costly abatement options.

Date of receipt of final manuscript: September 2011

1.0 Introduction

Worldwide aviation is expected to grow by just under 5 per cent per year for the next two decades (Airbus, 2009; Boeing, 2010). This growth will have environmental consequences via noise, air quality, and climate impacts (Mahashabde *et al.*, 2011). Potential mitigation methods include regulations and standards, technological improvements involving aircraft and engine performance, and/or the development of alternative fuels, operational improvements, and market-based policies. In regard to market-based policies, the House of Representatives passed the American Clean Energy and Security Act of 2009 (H.R. 2454, also known as Waxman-Markey Bill) on 22 June 2009. H.R. 2454 proposes an upstream cap-and-trade policy to curtail greenhouse gas (GHG) emissions. Such a policy would affect all US industries, as refineries would be required to purchase allowances for each potential ton of carbon dioxide (CO_2) emissions. In the long run, refiners will pass on these increased costs to consumers, such as airlines. Based on the specifications of H.R. 2454, this study analyses the impact of climate policy on aviation operations, financial outcomes, and emissions. Although H.R. 2454 failed to gain Senate approval in the 111th US Congress and thus did not become law, we use the specifications in H.R. 2454 as a representative climate policy. We justify this on two grounds. First, the 2020 emissions reduction in H.R. 2454 matches the 2020 emissions reduction pledged by the US in the Copenhagen Accord. Second, as the only climate legislation to pass a House or a Senate vote, H.R. 2454 provides a useful estimate of the specifications of a future US cap-and-trade policy should such a policy receive sufficient support to be adopted.

The impact of cap-and-trade programmes on aviation has been examined by several studies, which are summarised in Appendix 1. Most analyses focus on the emissions and economic impacts of the European Union (EU) Emissions Trading Scheme (ETS).[1] Other studies, also with an EU-ETS focus, examine legal issues associated with including aviation in cap-and-trade programmes (Oberthuer, 2003; Peterson, 2008; Haites, 2009) or the impact of climate policy on airline competition (Forsyth, 2008; Albers *et al.*, 2009; Scheelhaase *et al.*, 2010). To our knowledge, Hofer *et al.* (2010) is the only study to focus on the impact of a US cap-and-trade policy. Hofer *et al.* (2010) use a partial equilibrium model to simulate the environmental impacts of an assumed airfare increase. We contribute to this literature by analysing the impact of a cap-and-trade policy on US aviation using an economy-wide model and a detailed partial equilibrium model of the aviation industry. We use our economy-wide model to estimate the impact of a cap-and-trade policy (taking H.R. 2454 as a representative example) on the fuel price, the price of emissions allowances, and the overall level of economic activity. Given these predictions, a partial equilibrium model is employed to estimate changes in aviation emissions and operations. To our knowledge, we are the first to analyse the impact of climate policy on aviation by combining a climate policy model and a detailed aviation model. Although climate policy is designed to internalise negative externalities associated with GHGs, we

[1]See, for example, Wit *et al.* (2005); Boon *et al.* (2007); Ernst & Young (2007); Morrell (2007); Scheelhaase and Grimme (2007); Mendes (2008); Anger (2010); Hofer *et al.* (2010); Mayor and Tol (2010); and Vespermann and Wald (2010).

do not consider benefits from avoided climate damages. Thus, our study cannot be used to assess the overall effectiveness of climate policy.

This paper has four further sections. Our modelling framework is detailed in Section 2. Section 3 outlines the scenarios we consider. Modelling results are presented in Section 4. A sensitivity analysis is detailed in Section 5. The final section provides a short summary and conclusions.

2.0 Modelling Framework

Our analysis employs version 4 of the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005) and version 4.1.3 of the Aviation Environmental Portfolio Management Tool for Economics (APMT-E, MVA Consultancy, 2009). EPPA is used to determine the economy-wide impacts of climate policy and, given predicted changes in key variables simulated by EPPA, APMT-E calculates the impact of climate policy on aviation emissions and operations.

EPPA is a recursive dynamic, computable general equilibrium (CGE) model of the global economy that links GHG emissions to economic activity. The model is maintained by the Joint Program on the Science and Policy of Global Change at the Massachusetts Institute of Technology, and has been widely used to evaluate climate policies (see, for example, Paltsev *et al.*, 2007 and 2009).[2] EPPA models the world economy and identifies the US, fifteen other regions and nine sectors, including electricity and refined oil. Reflecting EPPA's focus on energy systems, electricity can be produced using conventional technologies (for example, electricity from coal and gas) and advanced technologies (for example, large-scale wind generation and electricity from biomass). Advanced technologies enter endogenously when they become economically competitive with existing technologies. Refined oil includes refining from crude oil, shale oil, and liquids from biomass, which compete on an economics basis and can be used for transportation. EPPA is calibrated using economic data from the Global Trade Analysis Project (GTAP) database (Dimaranan, 2006), energy data from the International Energy Agency (IEA, 2004), and non-CO_2 GHG and air pollutant data from the Emission Database for Global Atmospheric Research (EDGAR) 3.2 (Olivier and Berdowski, 2001; Bond *et al.*, 2004). The model is solved through time, in five-year increments, by imposing exogenous growth rates for population and labour productivity.

APMT-E is one of a suite of models developed by the Office of Environment and Energy at the Federal Aviation Administration (FAA) for assessment of aviation-related environmental effects. The model is designed to examine aviation industry responses to policy measures (see, for example, ICAO/GIACC, 2009; and CAEP, 2010). APMT-E is a global model that determines operations for country pair-stage length combinations, known as schedules. Most country pairs have one stage length, but some country pairs involving large countries have more than one stage length. For example, the US–UK

[2]The EPPA model is coded using the General Algebraic Modeling System (GAMS) and solved using the Mathematical Programming System for General Equilibrium Analysis (MPSGE). The model is available at http://globalchange.mit.edu/igsm/eppadl.html.

country pair has five stage lengths, reflecting geographic disparity in US points of departure or disembarkation. AMPT-E also identifies six world regions (North America, Latin America, and the Caribbean, Europe, Asia, and the Pacific, the Middle East and Africa), twenty-three route groups (for example, North Atlantic, Domestic US, North America–South America, and Europe–Africa), nine distance bands (for example, in kilometres, 0–926, 927–1,853, and 6,483–8,334), ten aircraft seat classes defined by the number of available seats (for example, 0–19, 20–50, and 211–300), and two carrier types (passenger and freight).

Aviation operations are determined in each year by retiring old aircraft based on retirement functions. The surviving fleet is then compared to forecast capacity requirements to determine capacity deficits by carrier region, distance band, and carrier type. Potential new aircraft, which are combinations of available airframes, engines, and seat configurations, are evaluated by calculating operational costs (including fuel, depreciation, finance and maintenance costs, and route and landing charges) per seat hour over the life of the aircraft. Once new aircraft are purchased to meet fleet deficits and added to the surviving aircraft, the fleet is deployed across schedules and operating costs are calculated. Assuming a constant absolute dollar markup on costs, cost calculations are used to derive air fares, which are combined with route group price elasticities to compute demand. The constant markup assumption implies that all costs associated with a cap-and-trade policy are passed on to consumers. Although airlines may absorb some short-run cost increases, doing so would challenge profitability in the long-run; thus such actions cannot be sustained. Consequently, a full pass-through assumption is commonly used in long-run assessments of the impact of cap-and-trade policies on aviation (see, for example, Anger and Köhler, 2010). APMT-E price elasticities, sourced from Kincaid and Tretheway (2007), represent the average response of business and leisure travellers, and vary by route group. Price elasticities range from -0.36 for the Transpacific route group to -0.84 for the Intra-European route group. After a solution is found, differences between actual and forecast demands are used to update demand projections for the next period.

Our APMT-E reference scenario mainly follows ICAO/GIACC (2009). Traffic and fleet forecasts are from the Forecast and Economic Analysis Support Group (FESG) at the International Civil Aviation Organization (ICAO), adjusted by the short-term FAA Terminal Area Forecast (TAF). Aircraft fuel efficiency rises by 1 per cent per year, as assumed in ICAO/GIACC (2009) forecasts. Airspace management improvements driven by Next Generation (NextGen) High Density Analysis are first implemented in the US and then in other regions with a five-year lag. NextGen improvements are assumed to result in detour reductions relative to great circle distances in the US of 3 per cent in 2015 and 10 per cent in 2025. Corresponding decreases for non-US regions occur in 2020 and 2030. Load factors, average stage lengths, and aircraft retirement schedules are consistent with FESG forecasts used for the eighth meeting of the Committee on Aviation Environmental Protection (CAEP/8).

The main influence of the representative case of H.R. 2454 on aviation is likely to occur via the bill's impact on the fuel price and the overall level of economic activity. Accordingly, in our policy scenarios, using output from EPPA, we change fuel prices and demand forecasts used by APMT-E. Guided by Gillen *et al.* (2002), we assume an income elasticity of demand of 1.4 to convert GDP changes estimated by EPPA into changes in aviation demand. As EPPA has a five-year time step and APMT-E is solved for each year, we use linear interpolation to generate an annual series for EPPA predictions.

3.0 Scenarios

We model climate policy in the US using H.R. 2454 as representative cap-and-trade policy. The first major action by the US Congress to address climate change, H.R. 2454 sets an economy-wide target for GHG emissions, measured in CO_2 equivalent (CO_2-e) units, released between 2012 and 2050.[3] The chief emissions reduction instrument in H.R. 2454 is a cap-and-trade system that would cover between 85 per cent and 90 per cent of all US emissions. Other provisions, such as efficiency programmes, target emissions from uncovered sectors. Following Paltsev *et al*. (2009a, Appendix C), we simplify analysis of the policy by assuming that the cap-and-trade programme applies to all sectors. The cap is gradually tightened through 2050. It is 80 per cent of 2005 emissions (5.6 gigatons, or Gt, of CO_2-e) in 2020, 58 per cent (4.2 Gt) in 2030, and 17 per cent (1.2 Gt) in 2050.

Under H.R. 2454, US emissions may exceed the above targets if carbon offsets are used. Offsets allow businesses to support eligible offset projects, as determined by the Environmental Protection Agency (EPA), in lieu of turning in allowances. Offsets are restricted to 2 Gt — comprising 1 Gt from domestic sources and 1 Gt from international sources — per year. We consider two offset scenarios to capture uncertainties concerning the evolution of the market for offsets and the impact of competition from foreign cap-and-trade programmes. In a ‘full offsets’ scenario, 2 Gt of offsets are available each year at a specified cost. In a ‘medium offsets’ case, we assume that the quantity of offsets available increases linearly from zero in 2012 to 2 Gt in 2050. Another provision in H.R. 2454, allowance banking, allows firms to over-comply in early years and bank the excess of allowances for use in later years. As the stringency of the emissions constraint increases over time in H.R. 2454, banking reduces compliance costs. When firms can bank allowances, optimal behaviour will equate the discounted price of CO_2 allowances across years. We assume a discount rate of 4 per cent, which is approximately equal to the average federal funds rate from 2000–10 plus a 1 per cent risk premium.

We model climate policies in other regions following a recent Energy Modeling Forum scenario (EMF, Clarke *et al*., 2009). In the EMF scenario, developed nations (excluding the US) gradually reduce emissions to 50 per cent below 1990 levels by 2050, and China, India, the Former Soviet Union, and South America begin curtailing emissions in 2030. A difference between H.R. 2454 and climate policy in the EU is that H.R. 2454 requires energy producers, such as oil refineries, to turn in allowances, while end users, such as airlines, are required to submit allowances in the EU-ETS. However, as we assume that costs are passed through to consumers, ‘upstream’ and ‘downstream’ policies produce identical results. Additionally, although allocation rules have distributional effects, in our analysis the value of emissions allowances represent windfall gains or losses, so allocation rules do not influence operating decisions.

[3] CO_2-e units measure concentrations of other GHGs, such as methane and nitrous oxide, relative to the climate impacts of one unit of CO_2 over a specified time period, usually 100 years.

A contentious issue in the application of climate policy to aviation is how a nation's climate policy will influence foreign carriers flying to and from that nation, as is evident from court action by the Air Transport Association (ATA) challenging the legality of requiring flights by US airlines to and from the EU to purchase allowances under the EU-ETS. In our analysis, airlines pay carbon charges embedded in fuel prices, so airlines are influenced by foreign cap-and-trade programmes when they purchase fuel abroad. For example, a US airline flying to the EU pays the US CO_2-e price when refuelling in the US and the EU CO_2-e price when refuelling in the EU.

In addition to CO_2 emissions, aviation operations may influence climate via emissions of non-CO_2 gases, and soot and sulfate particles, which alter the atmospheric concentration of GHGs. Although some additional effects contribute to warming and others to cooling, non-CO_2 effects are believed to contribute to warming in aggregate (Penner *et al.*, 1999; Lee *et al.*, 2010). Aviation climate impacts from non-CO_2 sources are sometimes characterised by a metric — known as a multiplier — that divides the total impact of aviation on climate by the CO_2 impact. Although proposals requiring airlines to purchase allowances for non-CO_2 effects have been discussed in policy circles, such as the European Parliament, it remains uncertain whether such measures will be applied. To capture these uncertainties, we consider multiplier coefficients of one and two. When the multiplier is one, non-CO_2 effects are not considered, while a multiplier of two is used to capture non-CO_2 effects in our analysis. We refer to simulations employing a multiplier of one as 'no aviation multiplier' scenarios and simulations with a multiplier of two as 'aviation multiplier' scenarios. To reflect the increased scarcity of allowances in multiplier scenarios, we reduce economy-wide emissions caps based on estimates of the contribution of aviation to aggregate GHG emissions from Lee *et al.* (2010).

To consider alternative offset and multiplier combinations, we implement four scenarios: full offsets with no aviation multiplier (F1); full offsets with an aviation multiplier (F2); medium offsets with no aviation multiplier (M1); and medium offsets with an aviation multiplier (M2). These scenarios capture a wide range of possible outcomes. The cap on cumulative emissions between 2012 and 2050 is 17 per cent lower in full offset scenarios than in medium offset scenarios, and policy-induced aviation fuel price increases in multiplier scenarios are more than twice as large as fuel price increases in no multiplier scenarios. To determine the impact of climate policy, we compare each scenario to a reference case in which climate policies are not implemented in any region.

4.0 Results

Table 1 reports per ton CO_2-e prices (\$/tCO_2-e), measured in 2005 dollars, and proportional changes in GDP due to climate policy in three years: 2015, 2030, and 2050. In the F1 scenario, the emissions price is \$7 in 2015 and rises by 4 per cent (our assumed discount rate) per year so that the price reaches \$13 by 2030 and \$29 by 2050. In the medium offsets scenario without an aviation multiplier, M1, CO_2-e prices are around three times larger than in the F1 scenario. In the two multiplier scenarios, F2 and M2, increased demand for allowances increases CO_2-e prices relative to the corresponding no multiplier scenarios, but only slightly (for example, in the medium offsets case, including an aviation multiplier increases the 2015 CO_2-e price from \$21.31 to \$22.25).

Table 1
US CO_2-e Prices (in 2005 Dollars), and Aviation Fuel Price and Demand Changes Relative to the Reference Scenario

	CO_2-e price ($/t$CO_2$-e)			GDP-induced demand change (%)			Fuel price change (%)		
Scenario	*2015*	*2030*	*2050*	*2015*	*2030*	*2050*	*2015*	*2030*	*2050*
F1	7.27	13.09	28.69	−0.11	−0.43	−0.95	3.26	2.67	2.76
F2	7.79	14.03	30.74	−0.12	−0.48	−1.15	6.96	7.25	10.20
M1	21.31	38.39	84.07	−0.31	−1.01	−1.83	9.95	10.50	15.61
M2	22.25	40.07	87.08	−0.33	−1.09	−1.95	20.86	24.12	37.98

The treatment of the aviation multiplier also has a small impact on GDP changes, which range from −0.11 per cent to −0.33 per cent in 2015 and from −0.95 per cent to −1.95 per cent in 2050.

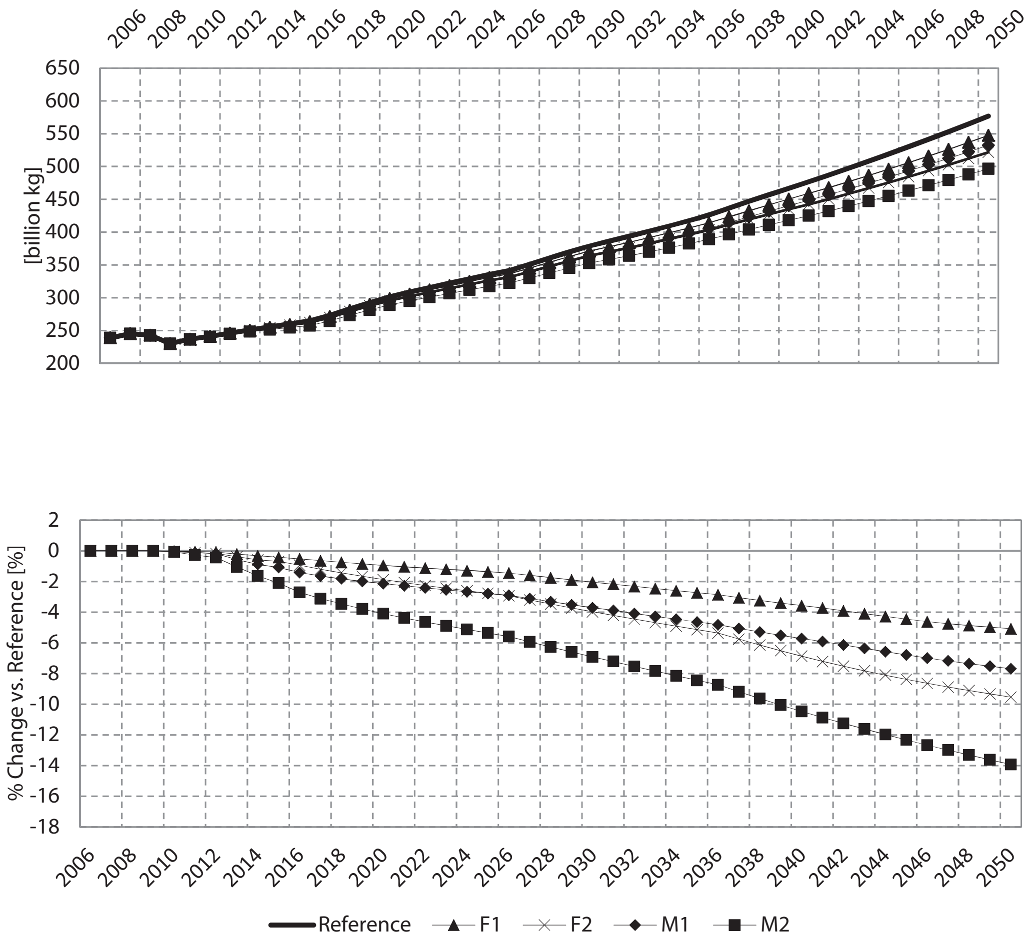
As noted above, H.R. 2454 will result in income-induced aviation demand changes and raise fuel prices. Income-induced demand changes are estimated by multiplying GDP changes by 1.4, to reflect an underlying income elasticity of demand. The largest income-induced demand decrease, which occurs in scenario M2 in 2050, is 1.95 per cent. This effect is modest compared to the impacts on demand of changes in fuel prices. Proportional changes in aviation fuel prices reflect the price of CO_2-e emissions and the number of allowances that must be purchased per ton of emissions. In scenario F1, the price of aviation fuel increases by 2.8 per cent in 2050 relative to the reference scenario, while the corresponding price increase in the M1 scenario is 15.6 per cent. Fuel price changes in multiplier scenarios are more than twice as large as in corresponding non-multiplier scenarios, as the multiplier is applied to a higher CO_2-e price than in no-multiplier scenarios.

How do changes in fuel prices influence aviation emissions and operations? Estimated annual aviation CO_2 emissions for the period 2012–50 under our reference and four policy scenarios are presented in Figure 1. In the reference scenario, CO_2 emissions increase from 250 million metric tons (Mt) in 2012 to 580 Mt in 2050, a 130 per cent increase. In policy scenarios, emissions trajectories are lower than in the reference case, but absolute emissions continue to increase substantially over the policy period by between 103 per cent in the most stringent scenario (M2) and 123 per cent in the least stringent scenario (F1). Thus, airlines respond to H.R. 2454 primarily by paying higher fuel prices rather than changing operations. This finding is consistent with other studies of the impact of climate policy on aviation emissions (see, for example, Mendes and Santos, 2008; Anger, 2010; and Vespermann and Wald, 2011).

Three explanations emerge for the small impact of H.R. 2454 on aviation emissions. First, the results indicate that aviation emissions mitigation options are more expensive than mitigation operations elsewhere. This is because, as fuel costs are a significant share — around 26 per cent (IATA, 2010) — of total aviation costs, airlines already operate closer to the fuel efficiency frontier than other industries. There is also limited scope for airlines to switch to alternative, low-emitting fuel sources compared to industries such as electricity, where coal can be replaced by several relatively inexpensive, low-carbon

Figure 1

Aviation CO_2 Emissions in the Reference and Policy Scenarios, 2006–50



energy sources. In our EPPA simulations, the largest proportional reduction in sectoral emissions is observed for electricity in all scenarios. In the M1 scenario, electricity emissions fall by 60 per cent relative to reference 2050 emissions. Second, despite large fuel price increases, demand changes induced by H.R. 2454 are small, as aviation demand is inelastic and the policy results in modest GDP changes. Third, as detailed below, the fleet becomes less fuel-efficient in our policy scenarios than in the reference case (even though fleet efficiency increases over time).

Our finding that H.R. 2454 reduces fleet efficiency warrants greater discussion. Fleet efficiency is gauged by fuel use per available ton kilometre (ATK). As there is a one-to-one mapping between fuel burn and CO_2 emissions, proportional changes in fuel use equal proportional changes in CO_2 emissions. In scenario M1, fuel per ATK increases by 0.14 per cent in 2015, 0.33 per cent in 2030 and 0.44 per cent in 2050. Similarly, in other scenarios, H.R. 2454 increases fuel per ATK relative to the reference through time.

Table 2
Changes in Fuel Use Per ATK Relative to the Reference

	Fuel use per ATK (%)		
Scenario	*2015*	*2030*	*2050*
F1	0.04	0.20	0.21
F2	0.11	0.45	0.60
M1	0.14	0.33	0.44
M2	0.27	0.72	0.99

We examine the drivers of our fleet efficiency results by displaying proportional changes in fleet size, average aircraft age, and average aircraft size relative to the reference in Table 3. In all scenarios, fewer new aircraft are purchased relative to the reference, so the number of aircraft in the fleet decreases and aircraft age increases on average. As new aircraft tend to be larger than existing aircraft, average aircraft size also decreases. Thus, the decrease in fleet efficiency is not only driven by airlines flying older, less efficient aircraft, but also, when selecting from the same set of technologies as in the reference scenario, purchasing smaller aircraft, which burn more fuel per ATK. In APMT-E, fleet efficiency changes are driven by two opposing forces: (i) rising fuel prices, which accelerate the introduction of new, more fuel-efficient aircraft; and (ii) reduced demand, which slows the introduction of new aircraft. In our simulations, the demand effect dominates the fuel-price effect.

A major concern for the aviation industry is the impact of H.R. 2454 on profitability. In this connection, the US Air Transport Association (ATA) estimates that the bill would increase US airline industry costs by $5 billion in 2012 and $10 billion in 2020 (Khun, 2009). Our results are in broad agreement with these numbers: estimated fuel cost increases range from $0.6 billion (F1) to $3.6 billion (M2) in 2012, and from $1.5 billion (F1) to $11.6 billion (M2) in 2020. However, cost increases in APMT-E are passed on to consumers via increased fares, so cost increases only influence profits via their impact on demand.

We report changes in financial indicators relative to the reference in Table 4. Unit (per seat mile) operating costs are affected by rising fuel prices and decreased average

Table 3
Changes in the Number of Aircraft in the Fleet, Average Aircraft Age, and Average Aircraft Size Relative to the Reference

	Number of aircraft (%)			Average age (%)			Average size (%)		
Scenario	*2015*	*2030*	*2050*	*2015*	*2030*	*2050*	*2015*	*2030*	*2050*
F1	−0.5	−1.3	−3.1	0.5	0.4	0.7	0.0	−0.2	−0.5
F2	−1.1	−2.3	−5.8	0.9	0.7	1.3	−0.1	−0.3	−1.0
M1	−1.7	−3.1	−6.1	1.3	0.9	1.0	−0.0	−0.1	−0.2
M2	−3.2	−5.4	−10.7	2.5	1.4	1.7	−0.0	−0.1	−0.5

Table 4
Changes in Total Operating Costs, Unit Costs and Operating Profits Relative to the Reference

	Operating costs (%)			*Unit costs (%)*			*Operating profits (%)*		
Scenario	*2015*	*2030*	*2050*	*2015*	*2030*	*2050*	*2015*	*2030*	*2050*
F1	0.1	−0.3	−1.3	0.6	2.0	4.2	−0.7	−2.2	−4.9
F2	0.5	0.7	1.3	1.3	5.4	12.6	−1.4	−4.2	−9.2
M1	0.6	−0.2	−1.0	1.8	4.0	7.7	−2.0	−3.8	−7.6
M2	1.5	1.5	2.8	4.0	9.9	20.6	−3.9	−7.1	−13.7

efficiency. Consequently, unit operating costs increase by 0.6 per cent in 2015, 2.0 per cent in 2030, and 4.2 per cent in 2050 in scenario F1, and larger cost increases are observed for scenarios with higher CO_2-e prices. As expected, profit changes are negatively correlated with fuel price changes. The largest proportional profit decreases, for scenario M2, are 3.9 per cent in 2015, 7.1 per cent in 2030, and 13.7 per cent in 2050, or (in 2006 dollars) \$0.2 billion in 2015, \$0.7 billion in 2030, and \$2.3 billion in 2050.

5.0 Sensitivity Analysis

An important finding in our analysis is that H.R. 2454 reduces fleet efficiency relative to the reference case. In this section, we investigate the robustness of this result to key components of AMPT-E. Specifically, we examine the sensitivity of results to aircraft retirement decisions, aircraft fuel-efficiency improvements, and income and price elasticities. As above, proportional changes in fuel use per ATK relative to the reference scenario are used to measure efficiency changes. Table 5 reports efficiency changes in 2015, 2030, and 2050 for our F1 scenario, for the base case and for each sensitivity analysis. Sensitivity results for other scenarios follow a similar pattern.

5.1 Aircraft retirement decisions

As noted in Section 2, aircraft retirements in APMT-E are based on FESG-CAEP8 retirement functions. Retirement curves are assumed to follow a Weibull distribution. Specifically, the probability that an aircraft of a certain age will survive in a given period under policy, ρ_{policy}, is:

$$\rho_{\text{policy}} = \frac{1}{\{1 + (1/\rho_{\text{base}} - 1) * e^{\lambda \Delta C}\}}, \tag{1}$$

where ρ_{base} is the survival probability in the FSEG forecast, ΔC is the cost of flying the existing aircraft minus the cost of flying new aircraft, and λ is the sensitivity of the survival probability to cost differences.

In a sensitivity analysis, we increase λ from 0.03 to 0.04, which decreases the survival probability of existing aircraft under climate policy, relative to our base F1 scenario. As illustrated in Table 5, earlier retirement of old aircraft decreases fuel per ATK relative to our base F1 scenario. However, changes in fleet fuel burn per ATK are small (fuel burn

Table 5
Changes in Fuel Use Per ATK Relative to the Reference for the F1 Scenario

Sensitivity scenario	*2015 (%)*	*2030 (%)*	*2050 (%)*
Base	0.04	0.20	0.21
Lower aircraft survival probability	0.08	0.17	0.16
Higher new aircraft efficiency (reference and policy)	0.08	0.23	0.23
Higher new aircraft efficiency (policy only)	−0.48	−4.04	−10.68
No income-induced demand change	0.03	0.16	0.21
Zero price elasticity demand	−0.42	−1.58	−2.70

relative to the reference case increases by 0.17 per cent in 2030 and 0.16 per cent in 2050, compared to 0.20 per cent in 2030 and 0.2 per cent in 2050 in our base F1 scenario).

5.2 New aircraft fuel efficiency

In another sensitivity analysis, we increase the scope for airlines to respond to rising fuel prices by purchasing new technologies. New aircraft fuel efficiency rises by 1 per cent per year in APMT-E. In a sensitivity analysis, we impose a 1.5 per cent annual fuel efficiency improvement, which we apply to both the reference and policy scenarios. With higher new aircraft efficiency, fuel use per ATK increases relative to the reference, as in our base F1 scenario.

We also consider a sensitivity analysis where higher fuel prices induced by H.R. 2454 spur development of new technologies. In this analysis, new aircraft efficiency improves by 1.5 per cent annually in the policy case and 1 per cent annually in the reference case. In this case, unlike in our base scenario, fleet fuel efficiency increases relative to the reference — by 0.48 per cent in 2015, 4.04 per cent in 2030, and 10.68 per cent in 2050. These efficiency changes are large, but not unexpected given that the growth rate for new aircraft efficiency is 50 per cent larger in the policy scenario than in the reference. This simulation indicates the importance of technology responses to price changes.

5.3 Income and price elasticities

H.R. 2454 slows the introduction of new aircraft by reducing the demand for aviation. Accordingly, in separate sensitivity analyses, we examine the impact of the income elasticity of demand and price elasticities of demand. In one analysis, we set the income elasticity of demand for aviation equal to zero, so GDP changes induced by climate policy do not influence aviation demand. Under such a scenario, fuel per ATK decreases relative to the base F1 scenario, but still increases relative to the reference scenario, by 0.21 per cent in 2050. In another analysis, we set the price elasticity of demand for aviation equal to zero. Under this extreme price–response assumption, fuel use per ATK, relative to the reference, decreases by 0.42 per cent in 2015, 1.58 per cent in 2030, and 2.70 per cent in 2050.

6.0 Conclusions

We examined the impact of climate policy on aviation emissions and economic outcomes in the US. We used H.R. 2454 as a representative cap-and-trade policy. Our analysis, benchmarked to ICAO/GIACC (2009) forecasts, estimated that aviation emissions between 2012 and 2050 will increase by between 103 per cent and 123 per cent under H.R. 2454, compared to 130 per cent without climate policy. These results indicate that aviation emissions abatement options are costly relative to mitigation options in other sectors. In the face of high abatement costs, it is less costly for aviation to fund abatement in other sectors than to reduce emissions. Key determinants of marginal abatement costs in APMT-E include the specification of new aircraft capital costs, fuel efficiency improvements, and retirement rates. Currently, there are limited opportunities for airlines to replace more CO_2-intensive energy sources with less CO_2-intensive energy sources, and to substitute between energy and other inputs.

Another noteworthy finding is that, under the set of assumptions in our framework, GDP and fuel price changes induced by H.R. 2454 reduce fleet efficiency relative to our reference case, as the demand effect outweighed the fuel-price effect. That is, the impact of reduced demand for aviation on new aircraft purchase decisions dominated incentives to purchase more efficient aircraft in the face of rising fuel prices. We examined the sensitivity of our results to several key modelling assumptions. In general, our finding that H.R. 2454 reduces average fleet efficiency is robust to plausible alternative modelling assumptions examined in our sensitivity analyses. However, our fleet efficiency results were overturned when we assumed that aviation demand was perfectly inelastic, and when we assumed that fuel price increases induced by H.R 2454 increased the fuel efficiency of new aircraft by 50 per cent, relative to the reference scenario.

Several caveats to our analysis should be noted. First, as we focused on long-run trends, adjustments associated with business cycles were not considered. In economic downturns, airlines may park old aircraft, which are replaced by new aircraft in high-growth periods rather than brought back into service. Second, our modelling framework did not capture some adjustments available to airlines using the existing fleet. For example, we did not allow airlines to retrofit seat configurations or use slower flight speeds in response to fuel price changes. Third, we did not consider how changes in air traffic management, induced by climate policy, might improve operations and reduce emissions. When these adjustments are considered, climate policy may have a larger positive impact on fleet efficiency than in our study. Future research will focus on these issues.

We close by cautioning that our results do not indicate that including the aviation sector in an economy-wide cap-and-trade system will be ineffective. As is well known, a cap-and-trade system reduces emissions where they are least costly to abate. Our results indicate that the aviation sector contributes to emissions targets mainly by funding (through purchasing permits) emissions reductions in sectors with lower cost abatement options. Additionally, we did not consider benefits from avoided climate damages, so our results cannot be used to assess the overall effectiveness of climate policy.

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Appendix 1: Literature overview

Several studies examine the impact of climate policy on aviation. To date, most papers focus on the EU-ETS. Some studies analyse the general implications of cap-and-trade schemes or carbon taxes. To our knowledge, only one study, Hofer *et al*. (2010), focuses on the US. Table A1 summarises the literature to date. Studies can be grouped into three categories: (1) papers focusing on aviation financial indicators and environmental benefits from reduced aviation emissions; (2) analyses of the competitive effects of carbon policies; and (3) studies that analyse legal and political aspects. Studies focusing on legal aspects include Oberthuer (2003), Peterson (2008), and Haites (2009). Studies examining the impact of climate policy on airline competition tend to analyse case studies (Forsyth, 2008; Albers *et al*., 2009; Scheelhaase *et al*., 2010). Papers that assess the financial and environmental implications of including aviation in climate policy either utilise existing models (Wit *et al*., 2005; Boon *et al*., 2007; Anger, 2010) or develop new models (Ernst & Young, 2007; Morrell, 2007; Scheelhaase and Grimme, 2007; Mendes, 2008; Hofer *et al*., 2010; Vespermann and Wald, 2011). All studies in this group use an assumed allowance price, except Anger (2010), who uses a dynamic macroeconomic model.

Table A1
Studies Evaluating the Impact of Climate Policy on Aviation

Study	*Methodology*	*Scope*	*Key assumptions*	*Key findings*
Anger (2010)	Dynamic macro.model	EU-ETS	Allowance prices €5–€40 per ton of CO_2; full cost pass-through; efficiency improvements of 1% p.a.	Air transport CO_2 emissions decrease by up to 7.4%, relative to baseline in 2020.
Boon *et al*. (2007)	AERO-MS model	EU-ETS	Allowance prices €15 to €45; 47.3% to 100% cost pass-through in 2020.	Evidence of perfect competition.
Ernst & Young (2007)	Simulation model	EU-ETS	Allowance prices €6–€60; 29% to 35% cost pass-through; fuel efficiency improvements of 1% p.a.	Airline profits decrease by €40 billion over the period 2011 to 2022.
Hofer *et al*. (2010)	Simulation model	Carbon tax on US aviation	Air fare increase of 2%; price elasticity of −1.15; cross-price elasticity (air/car) of 0.041%.	Five billion ton reduction in aviation emissions. Increase in vehicle emissions of 1.65 billion lbs (2,540 million additional passenger miles).
Mayor and Tol (2010)	Hamburg Tourism Model	EU-ETS; carbon taxes in some countries	EU-ETS allowance price €23, full cost pass-through; carbon taxes of €11–€45 in the Netherlands and €14–€54 in the UK.	The three policies reduce global welfare by €12.6 billion. Tourists shift away from the taxed areas.
Mendes and Santos (2008)	Simulation model	EU-ETS	Allowance prices €7, €15, and €30, full cost pass-through.	Demand reductions due to EU-ETS less than 2%. Small supply-side emissions reductions due to high abatement costs.
Morrell (2007)	Three UK case studies	EU-ETS	Allowance price $40; full cost pass-through.	Climate policy has a larger impact on low-cost carriers than full service airlines.
Scheelhaase and Grimme (2007)	Simulation model	EU-ETS	Allowance prices €15–€30; full cost pass-through; fuel efficiency improvements of 1% to 1.47% p.a.	Small cost increases due to the EU-ETS compared to recent fuel price rises; the EU-ETS creates competitive distortions.
Vespermann and Wald (2011)	Risk analysis software	EU-ETS	Allowance prices are normally distributed with an expected value of €25.	The EU-ETS reduces the annual growth of CO_2 emissions by about 1% per year; small financial impacts on aviation; small competition distortions.
Wit *et al*. (2005)	AERO-MS Model	EU-ETS	Allowance prices €10–€30; full/no cost pass-through; fuel efficiency improvements of 1% p.a.	Industry-wide CO_2 emissions reductions of 20–26 Mt (13%–22%) in 2012.

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