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AVIATION ENVIRONMENTAL POLICY ASSESSMENT THROUGH DYNAMIC SIMULATION

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Keywords: *Aviation, Environmental Policy, System Dynamics, Non-Equilibrium Economics*

Abstract

The desire to make better informed aviation environmental policy decisions has pushed the US Federal Aviation Administration to make a concerted effort to improve the state-of-the-art in aviation policy emissions modeling. This capability is designed to look at the effect of environmental policy decisions in an equilibrium future state. This improvement represents a tremendous increase in capability over the current state-of-the-art. However, there maybe times when a dynamic, non-equilibrium model will provide insight into potential outcomes that the equilibrium approach does not. This paper presents and demonstrates a possible structure for a non-equilibrium model using a System Dynamics approach.

1 Introduction

Recently, due to scientific and popular concern, more attention is being payed to potential anthropomorphic changes to the environment. These changes manifest themselves both locally and globally. In order to minimize man's impact a number of potential solution strategies have been proposed and implemented. This is especially true in the aviation community, which is a very visible source of environmental noise and emissions. As with any policy noise and emission mitigation schemes produce multiple direct and indirect effects on the industry being regulated. In the case of aviation only limited analysis has been done to-date to explore the benefits, costs, and effectiveness of regulations currently in effect.

The primary means for public policy to directly impact the aviation community is in the areas of noise and emissions certification requirements, noise limits for specific airports, fuel prices, and fees and taxes associated with each of the impacted airlines, manufacturers, and related businesses. With air-travel demand projected to continue growing for the foreseeable future, the impact of aviation on the environment is only likely to grow. Therefore, it is important to be able to better understand the impact of environmental policies on the aviation community, specifically businesses, manufacturers, and passengers, and society as a whole.

Aviation environmental policy is typically decided through the International Civil Aviation Organization's (ICAO) Committee on Aeronautical Environmental Protection (CAEP) and its members including the United States Federal Aviation Administration (FAA) and the counterpart organizations in the European Union. CAEP's purpose is to coordinate international efforts in this field and provide guidance to government agencies for environmental regulations. Due to previous limitations in these orgranizations' analysis capabilities it has not been possible to fully address the impact of different policy scenarios on the dynamic civil aviation market. For this reason the FAA has initiated several programs through its academic and industry partners to help address this issue.

These tools, which are ambitious in scope, are designed to analyze the cost-effectiveness and benefits-cost ratio of potential future policies. In order to do this the tools currently focus on a path *independent*, equilibrium forecasting method. In most cases this approach will capture the primary effects of a policy and allow for differentiation between policy scenarios. However, there may be cases where the path of change is of interest, or the ability to discern path dependent outcomes is useful. This paper presents a possible approach for these situations.

2 Background

To properly appreciate the difficulty of developing a complete benefit-cost model for international environmental policy making, it is useful to look at the history of aviation environmental policy making. This includes a history of both local, national, and international policies. These policies range from controls on actual emissions to certification requirements, or stringencies, that are placed upon newly certified aircraft. Additionally, since this paper will proffer a non-equilibrium, dynamic approach it is useful for the reader to have a basic understanding of the underlying technique that this approach will use, System Dynamics.

2.1 Previous Aviation and Environment Policy Studies

One of the primary goals of the international policy making process with regards to civil aviation, is to create a consistent set of rules for aircraft manufacturers and operators. To this end the ICAO signatories have used the CAEP process to produce a series of rules that apply to aviation throughout a large portion of the world. In the past CAEP actions have typically focused on stringencies. These are policies which focus on setting a certification standard for aircraft that are newly certified after a certain date. In the past the stringency based standards have typically focused on either noise or specific emission. As such CAEP has effectively taken an alternating approach where one round focuses on noise and the next on local emissions. The previous two CAEP rounds, known as CAEP 5 and 6 have focused upon noise and NO_X (nitrogen oxides) respectively. These policy decisions are ultimately recommended to the ICAO commission. If the commission adopts them they are added to Annex 16 of the ICAO convention [1, 2]

2.1.1 CAEP Practices

Past CAEP meetings have been supported by a series of task and working groups. One of the more important of these is the Forecasting and Economics Analysis Support Group (FESG). FESG has typically been the point of confluence for estimating future passenger and cargo demand, air traffic, and the cost of policy implementation. FESG has been supported by a series of working groups whose members prepare a series of noise and emissions analysis, and develop tool-sets for use by FESG and other CAEP groups. These groups have been instrumental in the development of past analysis and the tools to support them. Two of these tool/analyses suites are the Aviation Emissions and Evaluation Reduction Options Modeling System (AERO-MS) tool developed by the Netherlands for use in both CAEP and local policy analysis and the CAEP/6-Issue Paper/13 (CAEP/6-IP/13) emissions stringency analysis process. These two activities serve to illustrate the state-of-the-art in CAEP analysis

2.1.2 AERO-MS

AERO-MS was developed for the Dutch Civil Aviation Authority in the early 1990s [3]. It was accepted for certain analyses within the CAEP process and has since been used for a series of policy analyses including:

1. Aircraft technology
2. Air transport demand and traffic levels
3. Operating costs
4. Direct economic impact (global)
5. Economy-wide impacts (Netherlands only)
6. Concentrations of emissions
7. Global warming effects [4].

AERO-MS provides a fairly comprehensive capability to evaluate equilibrium effects of aviation environmental policies. However, there are a number of limitations which the FAA's toolset is designed to mitigate. First, AERO-MS was not developed to provide full benefits-cost analysis capability [4]. Second, AERO-MS's datum data set was populated with 1992 data. This poses a couple of concerns including the age of the datum data set, and the fact that 1992 is considered by many not to be a properly representative year. The future toolset will allow for variation and easy updating of the datum data-set. The AERO-MS model was considered for, but not used in, the CAEP/6-IP/13 analysis on NO_X stringency.

2.1.3 CAEP/6-IP/13

The FESG reported to the CAEP/6 meeting about the analysis of a series of stringency options for the reduction of NO_X emissions during the aircraft landing and take-off cycle (LTO) and CO_2 emissions [5]. CAEP was considering tighter standards for NOx emissions, and the study analyzed the economic costs and emissions benefits of several stringency options. Stringency relative to CAEP/4 standards were considered from no change (baseline) and in 5% increments up to a 30% reduction in allowed NOx.

In order to meet these stringencies, the model considered only engine technology changes. Six possible "Technology Levels" were identified, though only four were actually considered. These were:

- **TL1**: Minor change to existing engine – does not require complete recertification, assumed to result in a NOx reduction of less than 5%.
- **TL2**: Major change with scaled proven technology – known technology, applied within existing engine, maintains thrust and pressure ratio characteristics, requires engine recertification. Assumed to result in NOx reduction in 5 to 15% range.
- **TL5A**: New technology using current industry best practice – the technology exists at another manufacturer, requires an acquisition program.
- **TL5B**: New technology (beyond current best) – technology does not exist, requires extensive development program. Current research indicates that this would result in a fuel burn penalty, assumed to be 2%.

The NO_X and CO_2 emissions effect were modeled with the Emissions & Dispersion Modeling System (EDMS) and the Global Emissions Model (GEM) developed by Boeing. In addition to the pure effect on emissions, CAEP wished to perform a cost-effectiveness approach to determine which stringency provided the greatest return for the cost incurred. In order to perform this a series of cost assumptions were used. The most important are included here:

- Two parties: manufacturer and operator
- Cost are calculated where they occur, no translation into price of engine or fares
- Non-recurring technology acquisition cost paid for by manufacturers
- Recurring manufacturing, maintenance, operating costs paid for by operators

The non-recurring technology cost, in 2003 dollars was assumed to be:

- TL1: $10 million per engine family
- TL2: $50 million per engine type
- TL5A: $75-100 million per technology
- TL5B: $0.5-1 billion per technology

Recurring costs included:

- Production cost increase due to complexity and materials
    - TL1: No cost increase
    - TL2: $20,000 increase
    - TL5A: $40,000 increase
    - TL5B: $150,000 increase
- Maintenance cost increase due to complexity and materials

  - TL2: $0-2 ($1) increase in maintenance cost per engine flight hour (EFH)
  - TL5A: $4-5 ($4) per EFH

- Increase in spares due to split fleets
- Fuel consumption increase of 2% for TL5b engines
- Loss of value, per aircraft, in existing fleet

The IP/13 analysis also did not take into account any significant feedback loop that would effect the end equilibrium state. Neither did it have any provisions for non-equilibrium, path dependent economic analysis.

2.1.4 Improvements in Future Tools

The FAA has commissioned the development of a toolset to assist in future aviation policy making. This toolset which is to have the capability of modeling the full benefit-cost ratio of a proposed policy scenario in a technology driven interdependent manner consists of three separate, but complimentary tools:

- Aviation Environmental Portfolio Management Tool (APMT)
- Aviation Environmental Design Tool (AEDT)
- Environmental Design Space (EDS)

The purpose of these tools is to provide a broad equilibrium based approach to policy cost-benefit analysis. The general layout of APMT is shown in Fig. 1. This toolset, currently under development, is an extremely ambitious undertaking that will significantly advance the state-of-the-art, will not be able to fully explore the non-equilibrium path that policy effects may take.

2.2 System Dynamics

System dynamics is a method that emerged in the 1960s and 70s to tackle the rising concerns about unmanageable complexities in real existing systems and processes by using control system theory. This eventually was then termed "Industrial Dynamics". The system in the name originally referred to a industrial production and distribution system [7]. This was the first effort to model the dynamics of industrial system, hence the name. This initially was limited to supply chain systems but then was extended to organizational structures and project management.

System dynamics was eventually applied to much larger systems such as urban models [8] and global models [9]. In fact system dynamics models were the foundation of the work on limits to growth [10] and on urban growth, renewal, and traffic planning. It has since been applied to a large variety of problems and was able to provide insights into causes of failures, potential strategies, and policy choices that actually have the desired effects.

System dynamics builds on four foundations. The first foundation is information-feedback control theory, which has its roots in design and understanding of engineering control systems. This control theory is instead applied to systems that may not model real physical systems, but can represent any kind of system, including those that model the flow of real physical items, such as materials, money, and goods.

The second foundation is the modeling of the underlying decision-making processes. This means that such a model strives to capture a system in such a way that it includes any relevant decision-making processes and key variables that represent such choices.

The third foundation is the experimental approach to system analysis which attempts to take the underlying concepts and make them easily accessible. This is primarily done by representing each element of a system model visually to facilitate the overall understanding of the connectedness of all elements and their influence on each other. Models are generally created and shown using a standard visual representation [11].

The fourth and final foundation is the use of digital computer simulation. Forrester was the first to make extensive use of computer technology to simulate the system models he created. There are currently a number of commer-

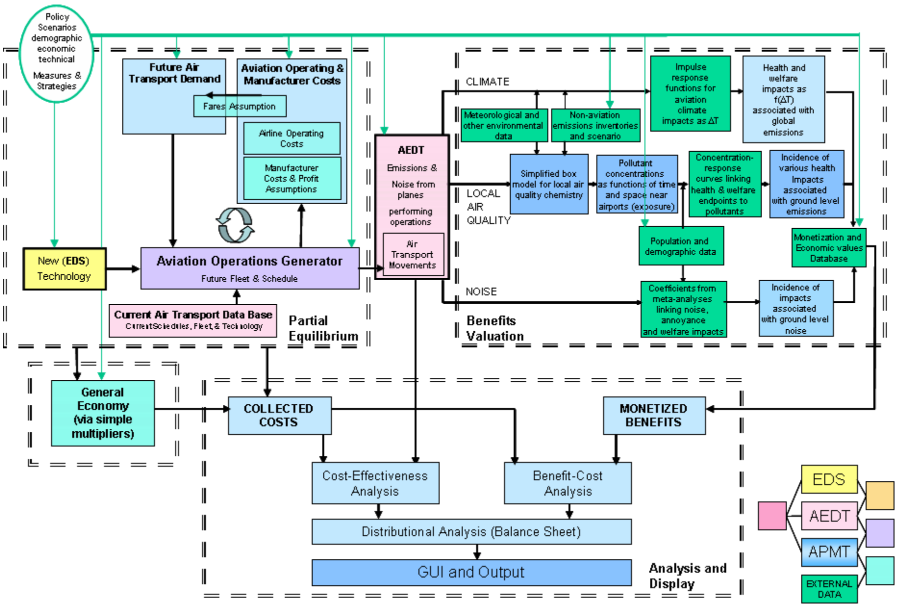

Fig. 1 Conceptual Flow of the Aviation Environmental Portfolio Management Tool [6]

cial computer System Dynamics software packages that readily allow visual model construction through a graphical interface. The package used for this example in this paper is Vensim $^{\text{TM}}$[12].

3 Proposed Approach

To demonstrate the potential usefulness of incorporating a path-dependent non-equilibrium approach to analyzing aviation environmental policy a simple dynamic demonstrator was constructed. This demonstrator, focuses on a small portion of the partial market linking a range of fee-based emissions policies with a simple monetized benefit analysis. This approach is not as complete as that envisioned for APMT [4, 6], however, it simulates a potential use of benefits-cost analysis in a non-equilibrium manner.

As another point of comparison, it was decided to use the basic premise of the CAEP/6-IP/13 analysis for the determination of technology performance, cost, and availability [5]. The primary differences between the IP/13 approach and that modeled here-in is that the cost-fare-demand relationship is modeled, and instead of NO_X stringency, a series of operating fees/charging schemes are evaluated.

3.1 Model Construction

The primary market model, which is designed to focus on the airline operations, demand, and the supply of current and new technology aircraft consists of eight major sections. The first, shown in Fig. 2, focuses on the combined fleets of both current and new technology aircraft. These fleets are modeled as “level" variables, that are fed by manufacturing queues and are drained by aircraft retirements.

Additionally, Fig. 2 contains the implementation of the NO_X charging mechanism. This mechanism is implemented as a charging level which is fed by a pulse function. The rise, height, and fall of this pulse function are governed by user controlled variables. The are also a series of user controlled variables presented in this view, which allow the user to determine the size of the inital fleet, the base fare, and the fuel cost (in $\$/gallon$).

Since this is a feedback model of the market, both for passengers and aircraft, the next two most important influence diagrams are for the setting of airfares and the determination of how many aircraft to order for the future. The fare balance loop is shown in Fig. 3. To balance the

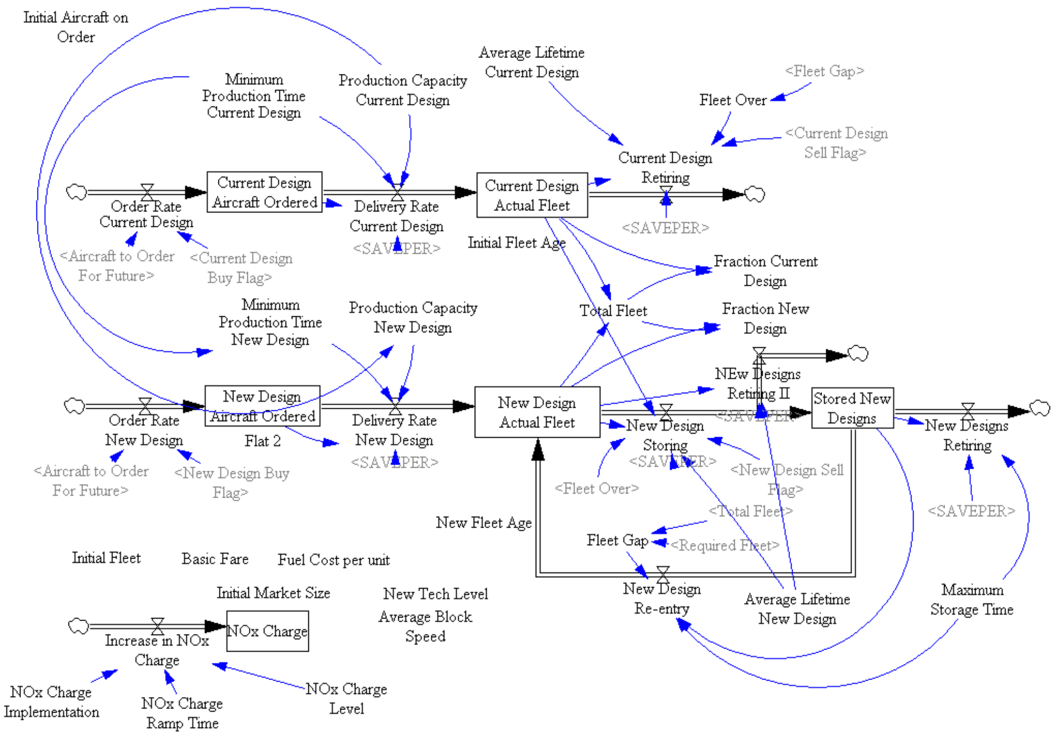

Fig. 2 Main Influence Diagram

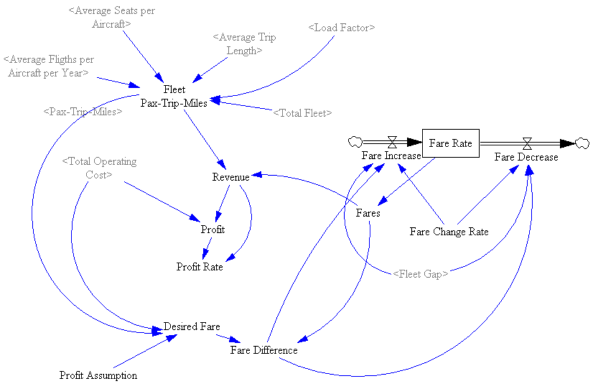

Fig. 3 Cost, Fare, Demand Balancing

fares a load factor is assumed, along with a desired profit margin. The fare is then determined to maintain both this load factor and the desired profit.

The most critical component of both the fare and fleet balance is the calculation of operating cost. This cost consists of fuel cost, any emissions charging, aircraft specific operating cost, and non-aircraft specific operating cost. In order to determine the cost of operations it is necessary to calculate both the total fuel burn and requisite emissions. Both of these loops are designed to determine the total fuel consumption and NO_X emissions for the entire fleet during each model step

Using the fuel burn and emissions it is possible to determine the total operating cost of the fleet. This is shown in Fig. 4 The total operating cost includes the both the cost of fuel and emissions, plus a series of per passenger-mile operating costs, both those that are aircraft specific and those that are non-specific. This cost allows for overall cost to be calculated. Using this overall cost in the influence diagram shown in Fig. 3 it is possible to calculate the airline profit/loss and the fare necessary to meet the desired profit margin.

The last major component of the notional model shown herein is the aircraft type selection. This is shown in Fig. 5. This selection method, considers both the operating and capital cost for each aircraft type. The type with the lowest total cost at a given time will be chosen for purchase. Also the aircraft type that is most expensive will be preferred for retirement or storage if the fleet

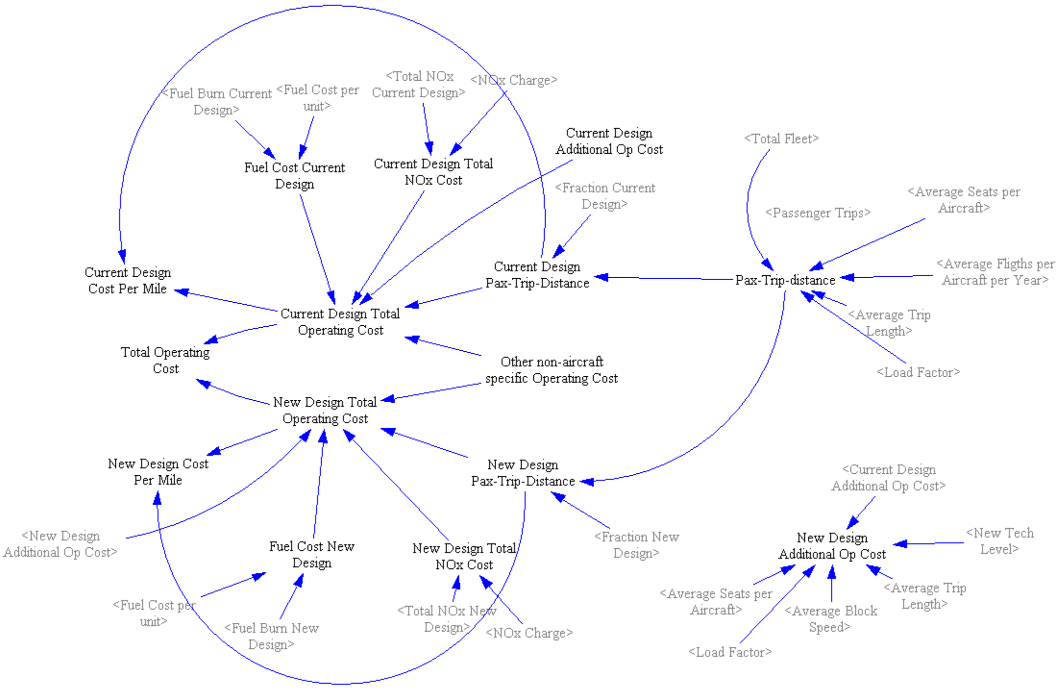

Fig. 4 Total Operating Cost Influence Diagram

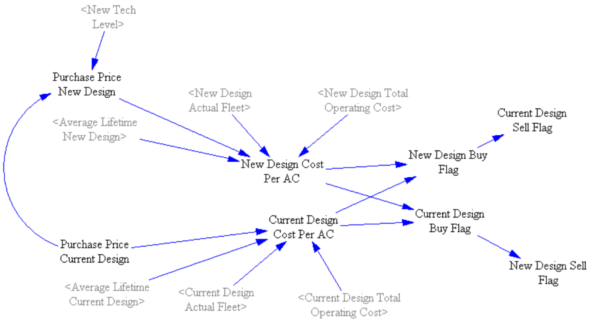

Fig. 5 Aircraft Purchase Preference Deterination

is larger than that required to meet the passenger demand.

3.2 Assumptions & Scenarios

In order to construct the model shown in Figs. 2 through 5 a series of assumptions was necessary. The primary source of these assumptions were those made in the CAEP/6-IP/13 study. These are listed earlier in this paper. The CAEP/6 assumptions primarily focus on deltas in aircraft fuel burn, emissions performance, and cost from current technology. They do not specify baseline values from which these deltas are taken. Therefore, an additional set of aircraft performance, fuel burn and emissions were also assumed. These were obtained from the values for a series of modern aircraft and engine combinations, contained within the *ICAO Emissions Databank* [13]. The basic starting values for the model are shown in Table 1.

Table 1 Model Assumptions

Variable	Value
Fuel Burn (gal/mile)	8
Fuel Cost ($/gallon)	2.2
LTO - NO_X Emissions (kg/mile)	0.2
Non-aircraft operating Cost ($/RPM)	0.04
Aircraft Operating Cost ($/RPM)	0.04
Aircraft Purchase Price ($million)	100

Since this model is notional, and only meant to show possible path dependent behaviors, the values selected for these inputs are only meant to be representative and should not be considered accurate for any current or future aircraft. Obviously, any release model that would be used for policy making would require a set of validated

Table 2 Scenario Variables

Variable	Distirbution	Param 1	Param 2	Param 3
Fuel Cost	Uniform	1.00	3.00	
NO_X Charge Level	Uniform	$0	$4	
NO_X Charge Implementation Date	Uniform	1	10	
NO_X Charge Ramp Time	Uniform	0	5	
New Technology Level	Vector	0	4	1
Initial Fleet	Uniform	250	1000	
Initial Order Backlog	Uniform	0	500	

and verified assumptions. Each of these scenarios varied the same set of control and noise values, including those listed in Table 1. The ranges for these variables are given in Table 2.

The demonstration of a system-dynamics approach to modeling aircraft environmental effects requires that demonstration scenarios be developed. These scenarios, which are detailed below, include a a series of technology level, one-at-a-time and all-at-a-time scenarios. To ensure that the model is behaving properly a simple extension of the datum assumptions into the future is necessary. The assumptions, listed in Table 1, also form the baseline scenario for future exploration.

Once the behavior is assessed for appropriateness it is possible to investigate the differences between a set of scenarios. The first one shown in the paper is the effect of differing technology levels on both fuel-burn and NO_X emissions through the simulation time. This is done with the NO_X charging level set to the high end of the range from Table 2. Several runs are performed with the new technology aircraft set to TL1, TL2, TL5a, and TL5b for runs 1 through 4 respectively.

Another illustrative set of scenarios is to run a Monte-Carlo analysis on the model either varying one of the scenario variables at at time or all of them at once. These random searches allow the user to determine which forward paths are available to the system; and therefore, how much of the future state is dependent upon the initial assumptions. The difference between the one-variable and all variables-at-a-time is that all-variables capture the interactions between the scenario variables, whereas the one-at-a-time looks only at the effect of the scenario variables themselves. The results of these scenarios are shown in the next section.

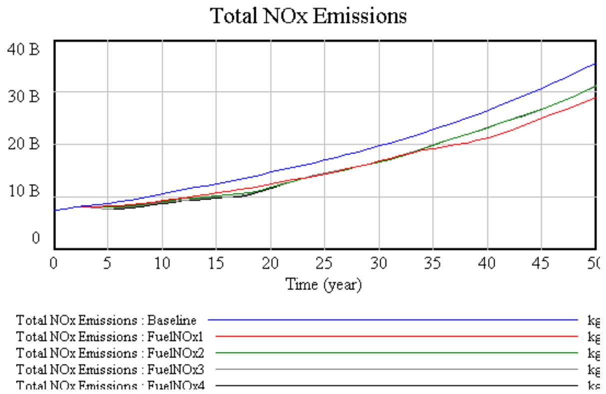

Fig. 6 Technology Level Effect on NO_X Emissions

4 Demonstration

Starting with the technology level assessment, described in the previous section, it is possible to illustrate the behavior of the model under the baseline conditions and those conditions in which both a NO_X charging scheme and different technology levels are implemented. Tracking both total fuel-burn and total NO_X emissions is useful as they show both the effect of charging and technology on NO_X emissions, plus the feedback through fares, demand, and fleet size on the total fuel-burn. These results are shown in Figs. 6 and 7 respectively.

The implementation of a NO_X charging scheme produces a both a delta in the absolute emissions of NO_X and also a change in the

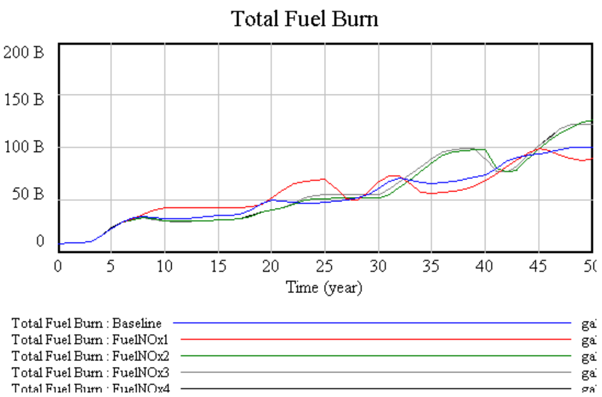

Fig. 7 Technology Level Effect on Fuel Burn

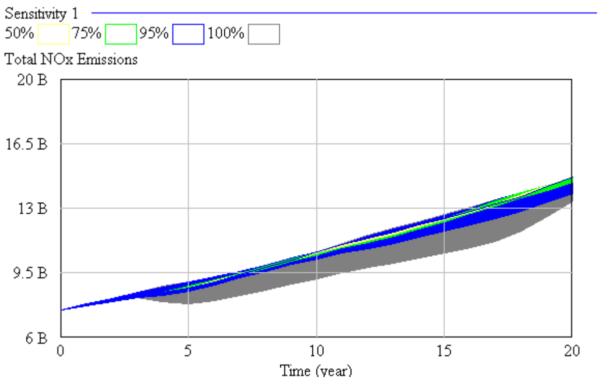

Fig. 8 One-On NO_X Sensitivity Analysis

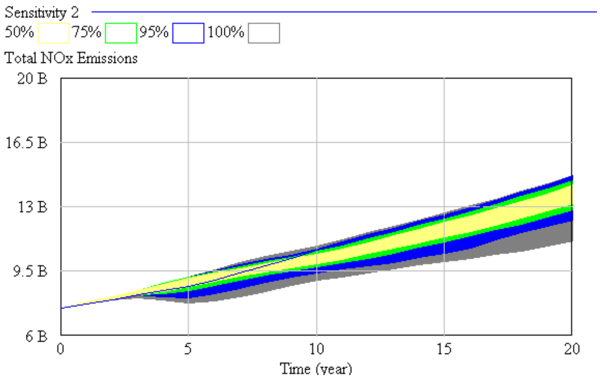

Fig. 9 All-On NO_X Sensitivity Analysis

growth of the emissions into the future. The effect of technology improvements on future NO_X emissions seems to be minimal when compared to the overall effect of a NO_X charging schema. Looking at the fuel-burn results, shown in Fig. 7, illustrates another interesting effect. In all situations the baseline value of fleet size is not sufficient to meet the passenger demand. This creates a fluctuating fuel burn as the number of aircraft in the fleet adjusts to the demanded amount of travel. This may or may not be representative of the effect that real-world decision making would have on the process of equilibration. Obviously more research needs to be done to determine the correctness of this phenomenon.

The two remaining examples presented in this paper are the Monte-Carlo analysis on One-on and All-on sensitivity analyses for total future NO_X emissions with respect to the variables given in Table 2. The results on the One-on and the All-on are shown in Figs. 8 and 9 respectively. Of interest is that the future total NO_X emissions are not just sensitive to the individual scenario variables, but also to the interactions between them. This is evident not only in the increased variability in the response between Fig. 8 and Fig. 9, but also in the increase of the range for future NO_X emissions.

5 Conclusion

The results demonstrated in this paper are just a small sample of the results produced by the model illustrated here-in; however, they do illustrate the range of capability that a system-dynamics model possesses. This capability, coupled with the desire to investigate market and model dynamics in a time-dependent and “non-equilibrium" manner provide a strong case for why dynamic models of future aviation and environmental policy decisions should be considered.

The model presented in this paper represents that starting point for future exploration of the capability. Currently the model represents a single aggregate aircraft type operated by a single airline type in a very median manner. Obviously, it would be ideal to have multiple different types of aircraft, each modeled in more detail than was contained in this example, operated by different types of airlines in different ways to compare different policy scenarios in a detailed manner.

The APMT plan calls for the inclusion of an aircraft modeling component, full partial market and general economy equilibrium models, the ability to calculate detailed environmental impacts and benefits valuations. Many of these analyses are not currently amenable to use in a full dynamic environment. However, it is within the realm of feasibility to include at least some amount of dynamic simulation in the future.

The inclusion of aircraft modeling and simulation in a dynamic environment has been demonstrated in a competitive environment by Pfänder and Mavris [14]. Further, a dynamic simulation of the US aviation market with security policy was included in the US Commercial Aviation Partnership's (USCAP) aviation security model [15]. The development of a full fledged dynamic environmental policy and technology model would require similar capabilities to these.

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