Reduced Thrust Takeoff Capability Demonstration Problem

Presented to: TRB AEDT/APMT Workshop #4

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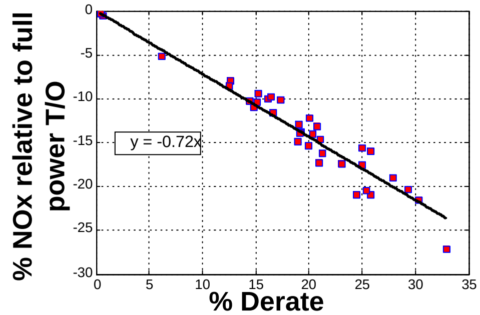
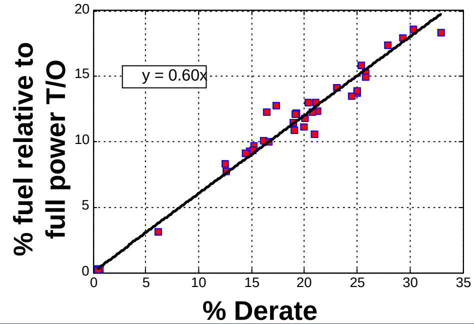
What is reduced thrust?

- Reduced thrust takeoff has become a *de facto* standard within the commercial airline industry
- Saves airline industry millions annually in aircraft/engine maintenance costs
- Most aircraft performance models used for environmental analysis do not account for this practice

Analysis of reduced thrust for AA B777 ops at LHR and LGW (contact: Ian Waitz, iaw@mit.edu)

- **Analyzed CFDR data from American Airlines**
- **Reports:**
  - CAEP/7-WG2-TG2/4-5-IP4
  - PARTNER-COE-2005-001 (at http://www.partner.aero)





Objectives of study

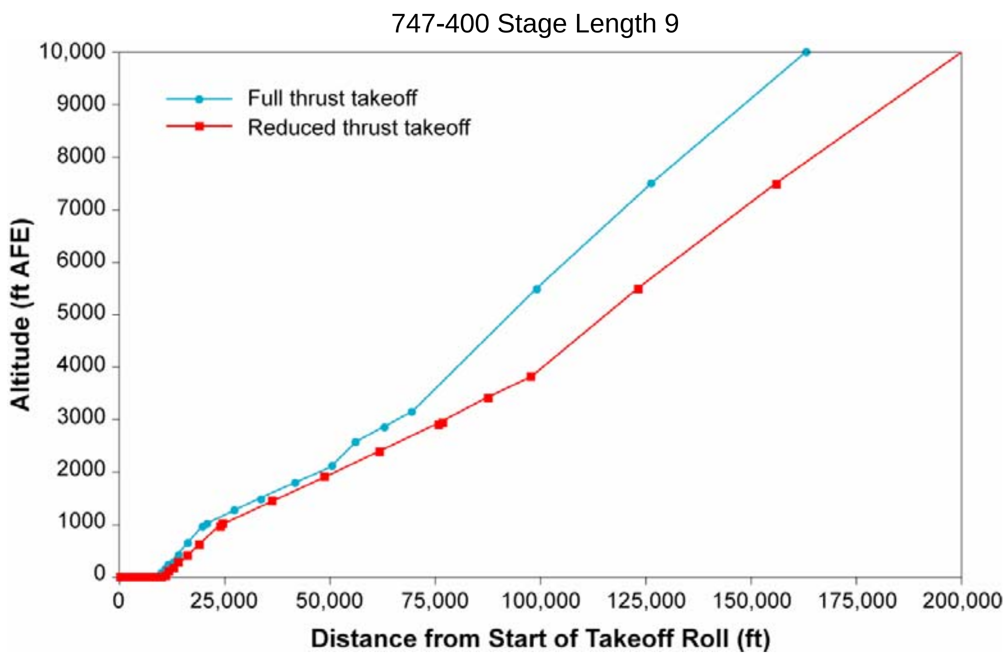
- **Develop improved methods for modeling aircraft performance for application in FAA's Aviation Environmental Design Tool (AEDT) and Aviation environmental Portfolio Management Tool (APMT)**

- **Intent of this capability demonstration is to identify model deficiencies while demonstrating a modeling capability**

Assumptions

- Global assessment
- Flight schedule information in the Official Airline Guide (OAG) for 10/18/05 used for the demonstration
- Baseline case assumed full-power takeoff
- Analysis scenario assumed 10% reduced thrust take-off for all aircraft types, regardless of airport
- Demonstration involves only AEDT and the APMT Benefits Valuation Block (BVB)
- Demonstration expands upon *sample problem* defined by ICAO/CAEP/WG2 by including health and welfare impact estimates

Profile changes that result



Responses Exercised

Response types	Response in Tool Suite	Reduced thrust
Block 1: APMT Partial Equilibrium Block		
Demand response to direct cost change	Yes	
Demand response to indirect cost change	Yes	(X)
Block 2: AEDT		
Noise	Yes	X
Emissions	Yes	X
Block 3: APMT Benefits Valuation Block		
Benefits of reduction climate impacts	Yes	X
Benefits of reduction noise impacts	Yes	X
Benefits of reduction local air quality impacts	Yes	X

Preliminary Results

- Noise
  - Number of people impacted with and without reduced thrust, **global**
  - Noise contours with and without reduced thrust, **94 US airports**
  - Valuation of noise impact with and without reduced thrust, **94 US airports**
- Local Air Quality **continental U.S. only**
  - Emissions with and without reduced thrust
  - Health impact of ozone due to NO_x
  - PM health impacts
- Climate **worldwide impacts**
  - Global average surface temperature change
  - Economic damage function (%GDP)
  - Net Present Value (NPV)
- Interdependencies
  - Relative changes in noise, LAQ, and climate impacts

Complex response to single input

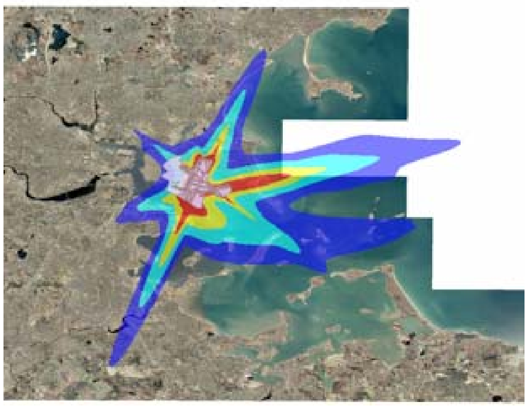
- **One aspect of airplane operations changed**
  - Throttle setting reduced during take-off
- **Emissions and noise change**
  - **CO_2 increases**
  - **NO_x decreases**
  - **SO_x increases**
  - **PM decreases**
  - **Noise decreases**
- **Also affects aviation economics (not addressed for this capability demonstration)**

NOISE RESULTS

Noise impact

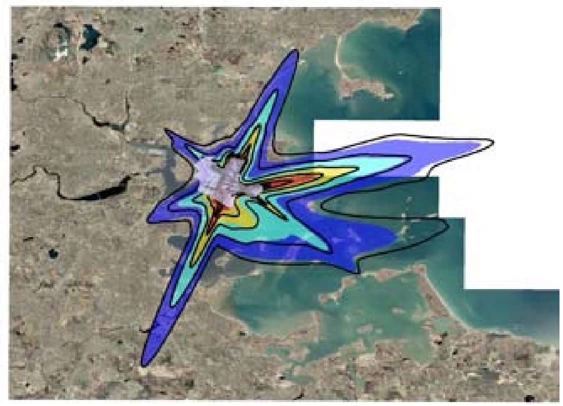
AEDT/MAGENTA provides noise contours for two scenarios

Baseline



Policy

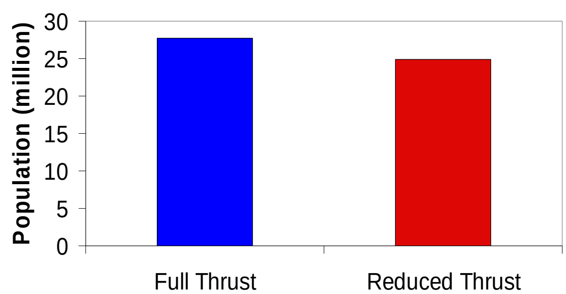
The black lines represent the baseline contours



Noise impact
(number of people impacted)

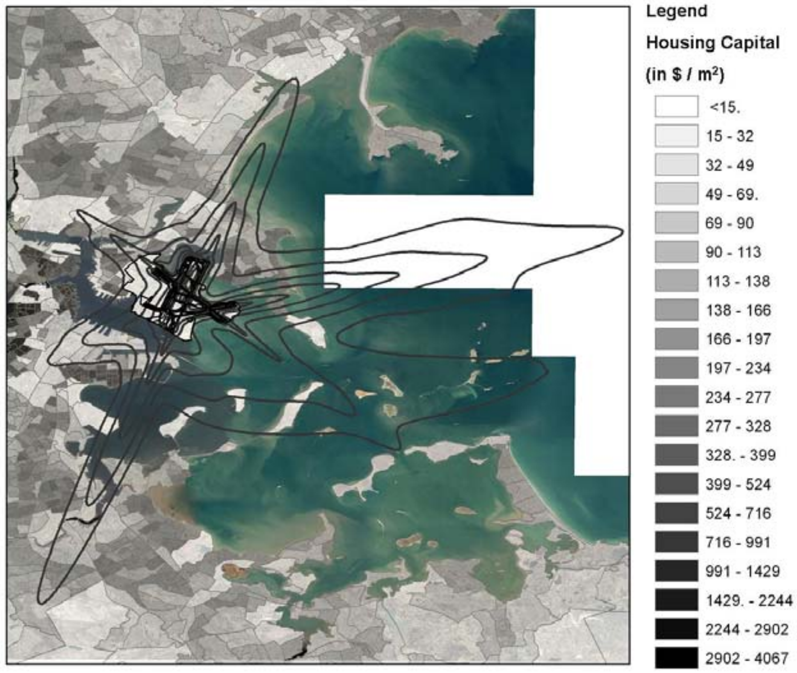
Population in 55 dB Contours in North America

Population in 55 dB Contours Worldwide



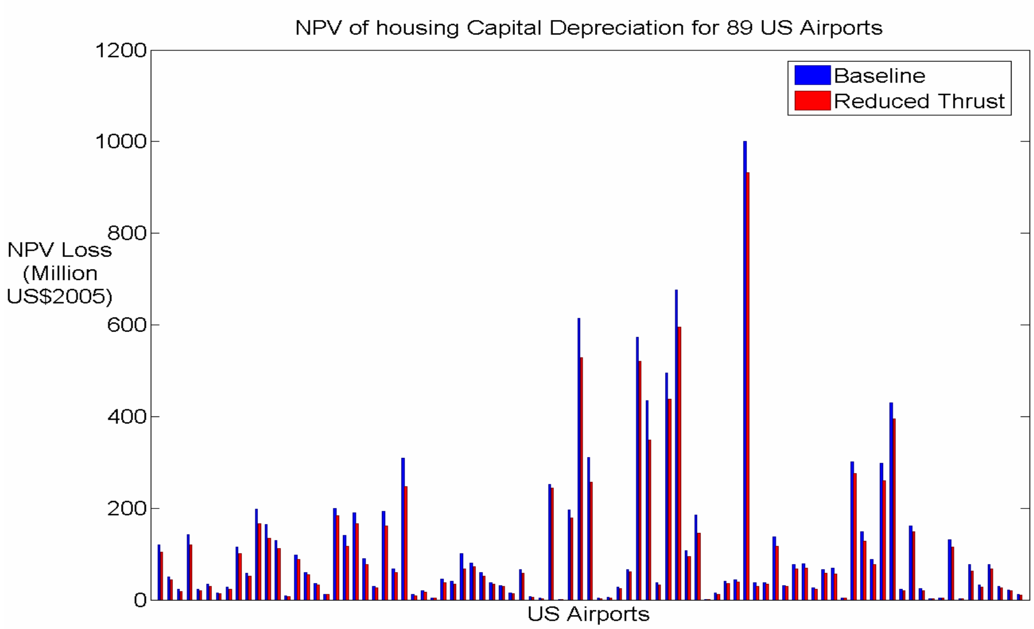
Noise impact

Noise Depreciation Index (NDI) used to correlate noise levels with housing capital depreciation



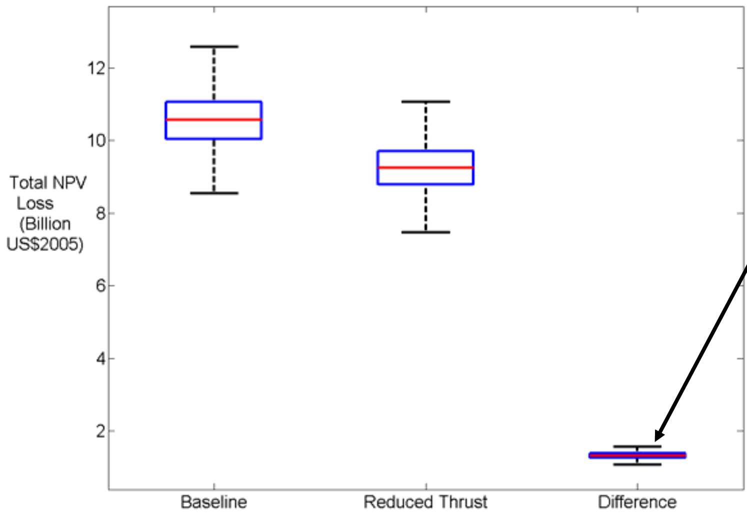
Noise impact

Net present value of depreciation of housing capital
(*MAGENTA Shell 1 U.S. airports only*)



Noise impact

- Aggregated monetary metric: Net Present Value of housing capital depreciation (94 MAGENTA Shell-1 U.S.airports)
- Monte-Carlo simulations provide measure of uncertainty



$NPV_{Policy\ effect}$

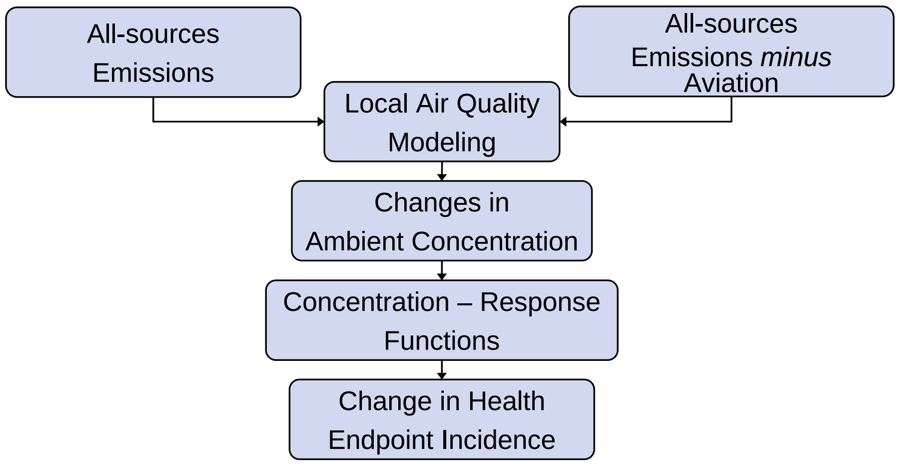
= 1.31 ± 0.34 US$B2005

("one time" benefit)

Local Air Quality

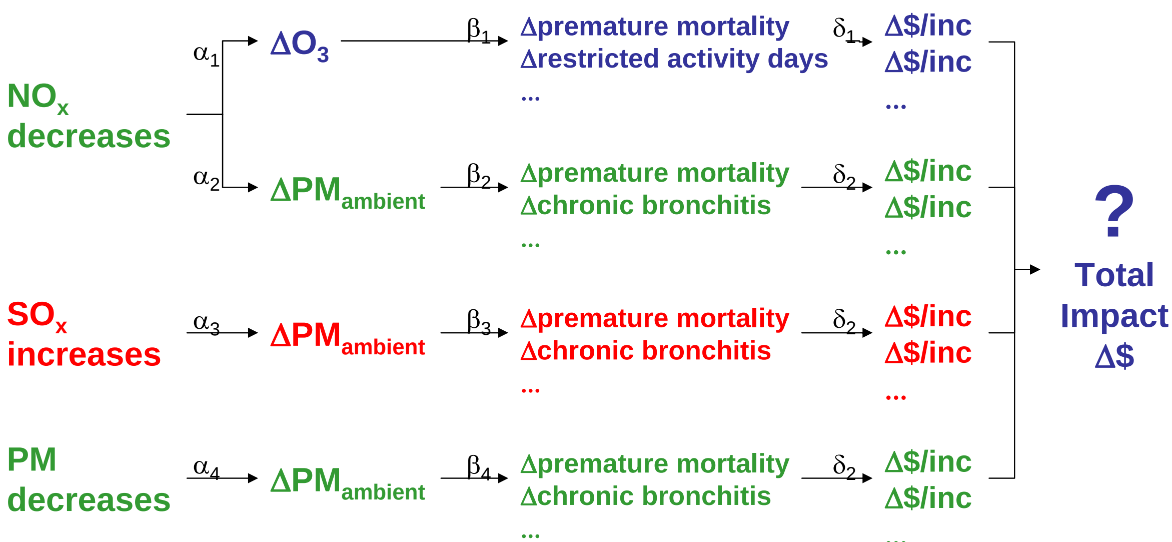
Health impacts assessment

- **Consistent with EPA and EU practice, only considering effects of ozone and PM**



$$\Delta\ \textbf{health costs} = \Delta\ \textbf{emissions} \times \frac{\Delta \textbf{ambient concentration}}{\Delta \textbf{emission}} \times \frac{\textbf{health incidence}}{\Delta \textbf{ambient concentration}} \times \frac{\textbf{cost}}{\textbf{health incidence}}$$

Impact pathway



Local air quality and climate response cannot be determined simply from observing changes in inventories

Relative Importance of Aviation Emissions (U.S. only)

	Total Anthropogenic [million tons]*	Total Aviation Baseline [million tons]**
Primary $PM_{2.5}$	6.6	0.0005 (0.008%)
NO_x	22	0.08 (0.4%)
SO_x	16	0.003 (0.02%)

*EPA 2001, latest available data
**Total aviation emissions below mixing height

EPA estimates of PM health effects

	Change in primary PM emissions (in million tons/year)	Change in nitrogen oxide (in million tons/year)	Change in sulfur dioxide (in million tons/year)	Change in premature mortality due to PM (annual cases)	Change in chronic bronchitis due to PM (annual cases)
Improvement from achieving 2006 National Ambient Air Quality Standards for PM*	**0.42**	**0.84**	**0.66**	**1200 to 13000**	**500 to 5000**
Clean Air Interstate Rule**	**N/A**	**1.37**	**3.75**	**9600**	**5200**

* EPA analysis, see http://www.epa.gov/ttn/ecas/ria.html
**EPA, Benefits of the Proposed Inter-State Air Quality Rule, EPA 452/-03-001 January 2004.

Reduced thrust emissions impact

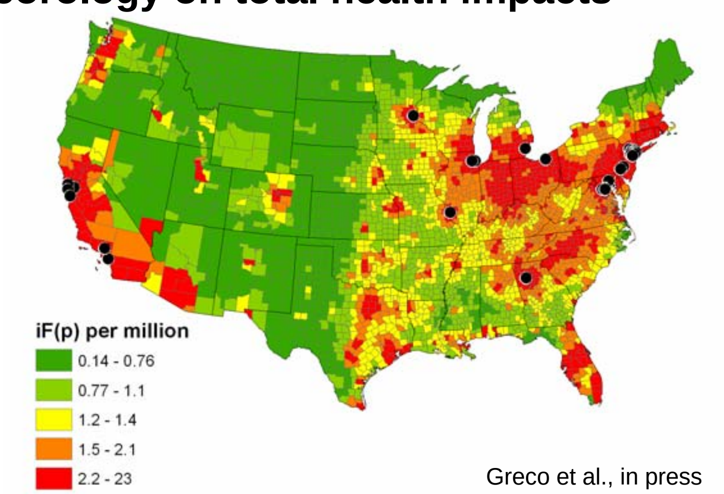
- **For 266 major airports within continental US, emissions below 3000 feet:**

Preliminary results do not cite or quote

Emissions below mixing height (in 10^3 ton/year)	Nitrogen Oxides (NO_x)	Sulfur Dioxide (SO_2)	Primary Particulate Matter
Baseline Full thrust	**77.0**	**2.93**	**0.46**
Policy Reduced thrust	**75.9**	**3.08**	**0.42**

PM health impacts

- **Area source $PM_{2.5}$ population exposures per unit emissions from Levy (Harvard School of Public Health) used to estimate impact of population patterns, meteorology on total health impacts**



Greco et al., in press

Harvard School of Public Health Intake Fraction method*

- **Source - Receptor Matrix**
  - Regression-based model derived from high fidelity atmospheric modeling tool (CRDM*)
  - Intake fraction coefficients **relate nationwide population exposures to county-level PM emissions**
- **Modeling of primary PM as well as secondary NO_x and sulfates**

* **Greco SL, Wilson AM, Spengler JD, Levy JI. Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States, Atmos Environ, in press.**

* * **Climate Regional Dispersion Model (CRDM)**

Local air quality impact of aviation PM (*cases per year*)

Preliminary results do not cite or quote

PM-related Endpoints	Baseline: Full Thrust	Policy: Reduced Thrust
Premature mortality:		
Long-term exposure (adults age 30+)	276	272
Long-term exposure (infants age <1 yr)	2	1.97
Chronic bronchitis	114	112
Hospital admissions-respiratory	83.5	82.3
Hospital admission-cardiovascular	86.5	85.3
Lower respiratory symptoms (children 5-14)	766	762
Emergency room visits for asthma	166	163
Asthma attacks-days of bronchodilator use	1,527,830	1,504,937
Minor restricted activity days	112,316	110,633

Local Air Quality PM impact

- **Aviation - related nationwide health impact of primary and secondary $PM_{2.5}$ by particle type**

Preliminary results do not cite or quote

Health impact of aviation (in cases per year)	Premature mortality (including infant)			Chronic bronchitis		
	PM-pri	NO_x Secondary PM	SO_x Secondary PM	PM-pri	NO_x Secondary PM	SO_x Secondary PM
Baseline Full thrust	40.7	182.6	55.2	16.7	74.8	22.6
Policy Reduced thrust	37.2	179.0	58.0	15.3	73.3	23.8

Local Air Quality PM impact

- **Aggregate non-monetary metrics derived from estimates of aviation pollution effects**

Preliminary results do not cite or quote

	Premature mortality (yearly cases per ton)	Chronic bronchitis (yearly cases per ton)
Primary PM	8.8×10^{-2}	3.6×10^{-2}
Sulfur Dioxide	1.9×10^{-2}	0.77×10^{-2}
Nitrogen Oxides	0.25×10^{-2}	0.1×10^{-2}

Yearly economic value of PM impact

Preliminary results do not cite or quote

Economic value PM-related Endpoints (US$M)	Baseline: Full Thrust	Policy: Reduced Thrust
Premature mortality:		
Long-term exposure (adults age 30+)	1,735	1,708
Long-term exposure (infants age <1 yr)	12.6	12.4
Chronic bronchitis	23.5	23.2
Hospital admissions-respiratory	0.061	0.060
Hospital admission-cardiovascular	0.188	0.185
Lower respiratory symptoms (children 5-14)	0.233	0.232
Emergency room visits for asthma	0.120	0.119
Asthma attacks-days of bronchodilator use	1.66	1.63
Minor restricted activity days	4.63	4.56

Local Air Quality PM impact

- **Yearly monetary value* of aviation - related nationwide health impact of primary and secondary $PM_{2.5}$ by particle type**

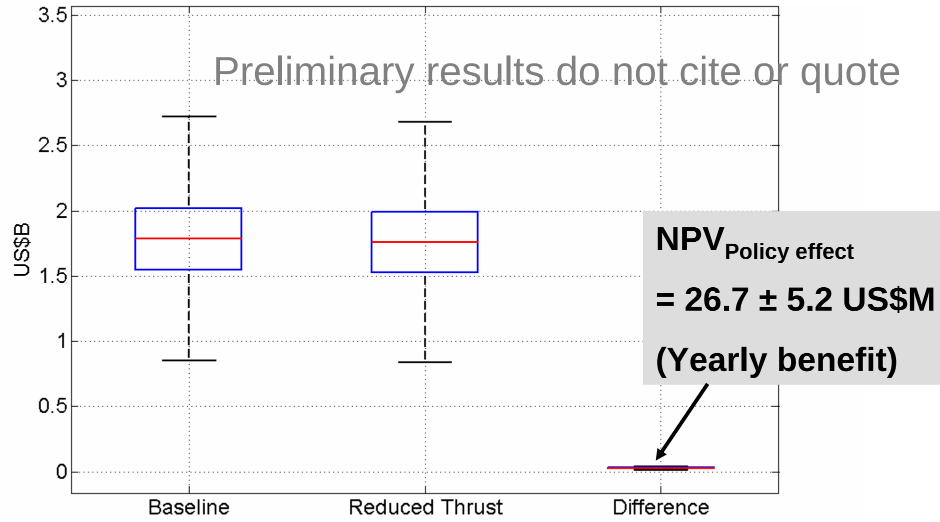
Preliminary results do not cite or quote

Monetary value of health impact of aviation (in million $US)	Premature mortality (including infant)			Chronic bronchitis		
	PM-pri	NO_x Secondary PM	SO_x Secondary PM	PM-pri	NO_x Secondary PM	SO_x Secondary PM
Baseline Full thrust	256	1150	348	3.4	15.4	4.7
Policy Reduced thrust	235	1128	364	3.1	15.1	4.9

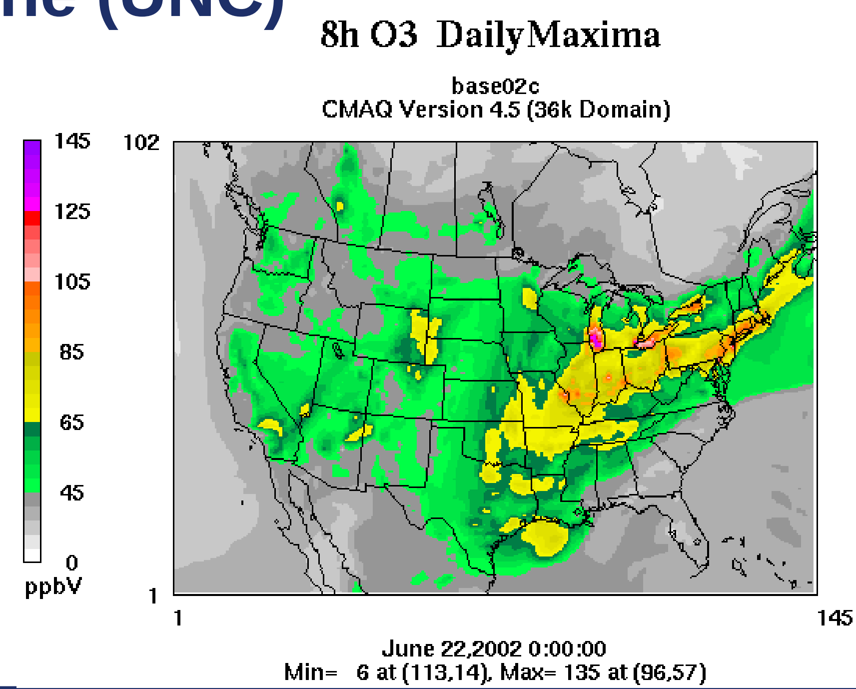
* Monetary values used:
Value of a Statistical L = 6,3 million $US
New case of chronic bronchitis = 200 k$ (ref. ExternE)

Local Air Quality (PM) impact

- Aggregated monetary metric: Net Present Value of policy effect
- Monte-Carlo simulations provide measure of uncertainty

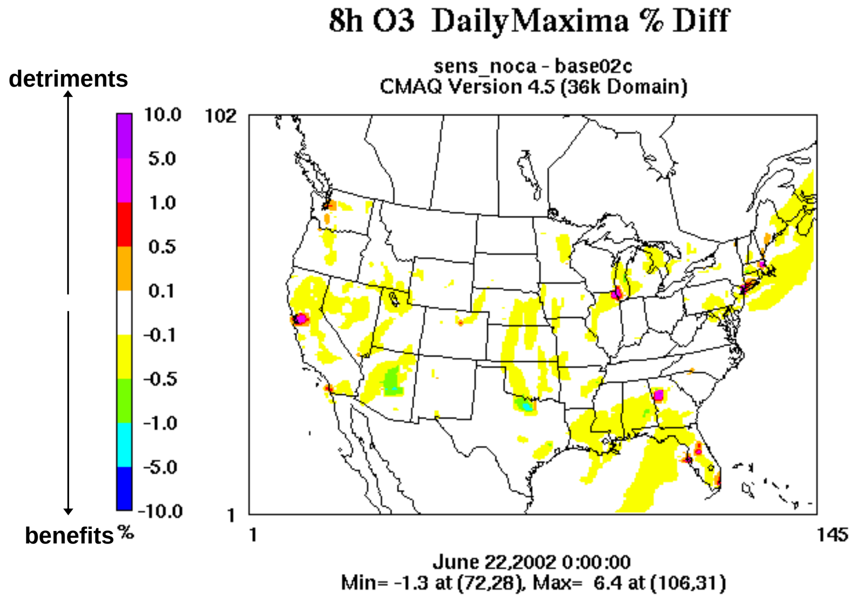


CMAQ estimated Daily Max 8h Ozone (UNC)



Change in CMAQ estimated Daily Max 8h Ozone (due to removing commercial aircraft)

Removing aviation emissions leads to ozone benefits at regional scales, but detriments near some urban cores



Ozone Impact

- Aviation health effects are largely dominated by PM
- Ozone impacts estimated based on CMAQ results

Cases per year*	PM impacts	Ozone impacts
Premature Mortality	~300	4
Restricted Activity Days	~100,000	3,000

* Calculated for four month ozone season

Ozone monetary impact

- **Aviation health effects are largely dominated by PM**

	PM impacts	Ozone impacts
Annual Costs (in US$B)	~1.75	0.03

- **Ozone impact is about 2% of total local air quality impact**

Local Air Quality impact

- **Aggregate metrics derived from estimates of aviation pollution effects**

Preliminary results do not cite or quote

	Primary PM	SO_x via PM	NO_x via PM	NO_x via Ozone*
Total health impact of pollutant ($ per kg emitted)	565	120	16	1.2
Amount emitted (10^3 tons per year)	0.46	2.93	77.0	77.0
Cost ($M per year)	240	320	1120	84

*Total ozone health impact divided by total NO_x emissions

Local Air Quality impact

- **Monetary value of aviation - related nationwide health impact of ozone and primary and secondary $PM_{2.5}$ total**

Preliminary results do not cite or quote

	Baseline Full thrust	Policy Reduced thrust
Monetary value of PM health impact (in billion $US/year)	1.78	1.76
Monetary value of ozone health impact (in billion $US/year)	<<PM	<<PM

Local Air Quality impact

- **Comparison to EPA's regulatory impact analysis: NAAQS and the Clean Air Interstate Rule**

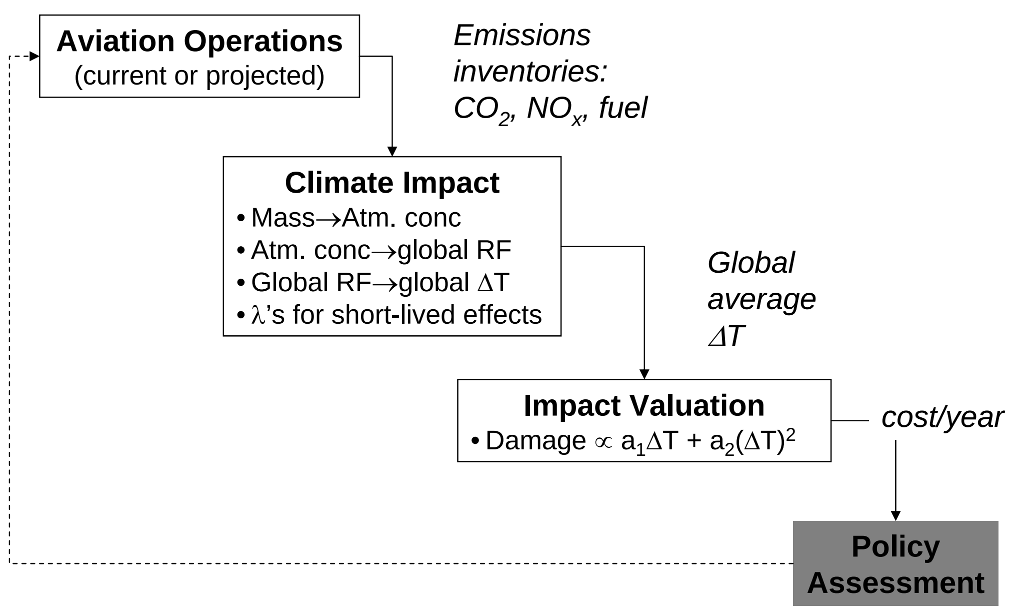
	Change in primary PM emissions (in million tons/year)	Change in nitrogen oxide (in million tons/year)	Change in sulfur dioxide (in million tons/year)	Change in premature mortality due to PM (annual cases)	Change in chronic bronchitis due to PM (annual cases)
Improvement from achieving 2006 National Ambient Air Quality Standards for PM*	0.42	0.84	0.66	1200 to 13000	500 to 5000
CAIR**	N/A	1.37	3.75	9600	5200
Aviation with full thrust minus reduced thrust	0.00004	0.0011	-0.00015	3.6	1.5

Preliminary results do not cite or quote

* EPA analysis, see http://www.epa.gov/ttn/ecas/ria.html
**EPA, Benefits of the Proposed Inter-State Air Quality Rule, EPA 452/-03-001 January 2004.

CLIMATE CHANGE

Simplified methods for valuing the impact of aviation on climate



Simplified methods for valuing the impact of aviation on climate

Aviation Operations
(current or projected)

Emissions inventories: CO_2, NO_x, fuel

IPCC IS92a, IS92c, IS92e for background CO_2

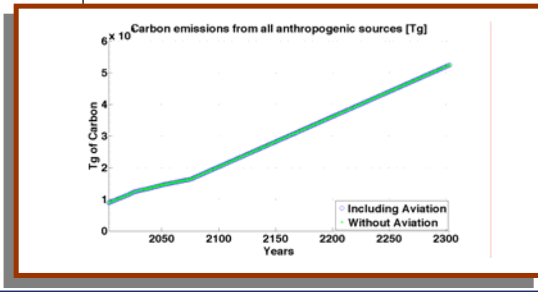
Climate Impact
- Mass→Atm. conc
- Atm. conc→global RF
- Global RF→global ΔT
- λ's for short-lived effects

Global average ΔT

Impact Valuation
- Damage ∝ $a_1\Delta T + a_2(\Delta T)^2$

cost/year

Policy Assessment



Simplified methods for valuing the impact of aviation on climate

Aviation Operations
(current or projected)

Emissions inventories: CO_2, NO_x, fu

CO_2 impulse responses from

$$\Delta X_{CO_2}(t) = Q_{CO_2}\left[\alpha_1 + \sum_{j=2}^{n_j} \alpha_j e^{-t/\tau_j}\right]$$

Climate Impact
- Mass→Atm. conc
- Atm. conc→global RF
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Global average ΔT

Impact Valuation
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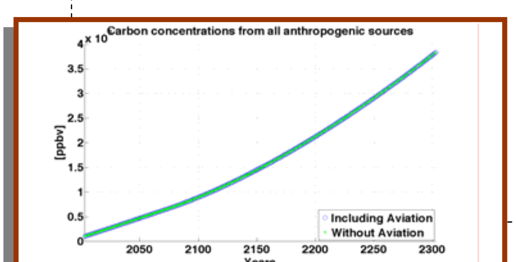
cost/year

Policy Assessment



Simplified methods for valuing the impact of aviation on climate

Aviation Operations
(current or projected)

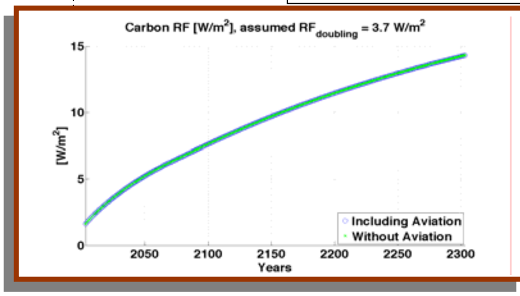
Emissions inventories: CO_2, NO_x,

IPCC (1996):

$$RF^*(t_0,t) = \frac{\ln\left(1+\frac{\Delta X_{CO_2}(t_0,t)}{CO_{2Ref}}\right)}{\ln(2)}$$

Climate Impact
- Mass→Atm. conc
- Atm. conc→global RF
- Global RF→global ΔT
- λ's for short-lived effects

Global average ΔT



Impact Valuation
- Damage ∝ $a_1\Delta T + a_2(\Delta T)^2$

cost/year

Policy Assessment

Simplified methods for valuing the impact of aviation on climate

Aviation Operations
(current or projected)

Emissions inventories: CO_2, NO_x, fu

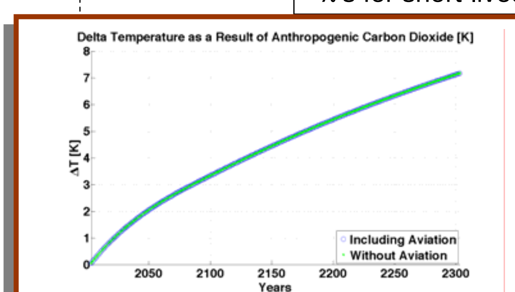
ΔT impulse responses from

Hooss et al. (2001)
Shine et al. (2005)

$$\Delta T(t) = \sum_{i=1}^{n} \alpha_i e^{-t/\tau_i} \cdot RF^*(t)$$

Climate Impact
- Mass→Atm. conc
- Atm. conc→global RF
- Global RF→global ΔT
- λ's for short-lived effects

ΔT



Impact Valuation
- Damage ∝ $a_1\Delta T + a_2(\Delta T)^2$

cost/year

Policy Assessment

Simplified methods for valuing the impact of aviation on climate

Aviation Operations
(current or projected)

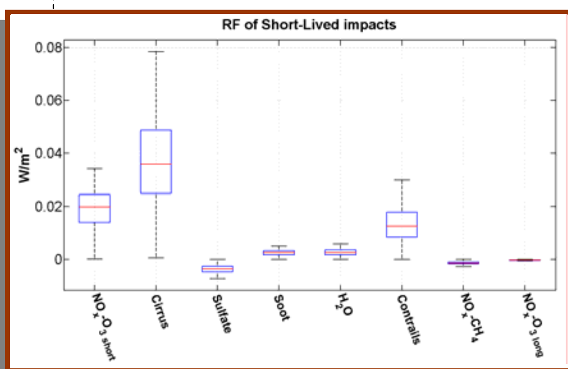
Emissions inventories: CO_2, NO_x, f

Short-lived effects following Sausen and Schumann (2000)

$$RF^{*}_{short}(t) = \frac{\lambda_{short}}{\lambda_{CO_2}} \cdot \frac{RF^{ref}_{short}}{RF_{2XCO_2}} \cdot \frac{Q_{short}(t)}{Q^{ref}_{short}}$$

Climate Impact
- Mass→Atm. conc
- Atm. conc→global RF
- Global RF→global ΔT
- λ's for short-lived effects

Global average ΔT



Impact Valuation
- Damage ∝ $a_1\Delta T + a_2(\Delta T)^2$

cost/year

Policy Assessment

Simplified methods for valuing the impact of aviation on climate

Linear damage potential, Shine et al. (2005)

$$LDP(t) = \Delta T_{aviation}(t)$$

Nordhaus and Boyer (2000) damage function:

$$D_J(t) = a_{1,J}\Delta T_{1900}(t) + a_{2,J}\Delta T_{1900}(t)^2$$

$$D_{aviation}(t) = D_{IS92}(t) - D_{IS92-aviation}(t)$$

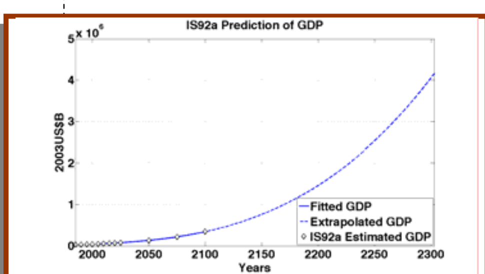
GDP(t) from IS92 scenarios

Discount rates 0%, 1%, 3%, 5%, 7%

Aviation Operations
(current or projected)

Climate Impact
- Mass→...
- Atm. c...
- Global ...
- λ's for short-lived effects

ΔT



Impact Valuation
- Damage ∝ $a_1\Delta T + a_2(\Delta T)^2$

cost/year

Policy Assessment

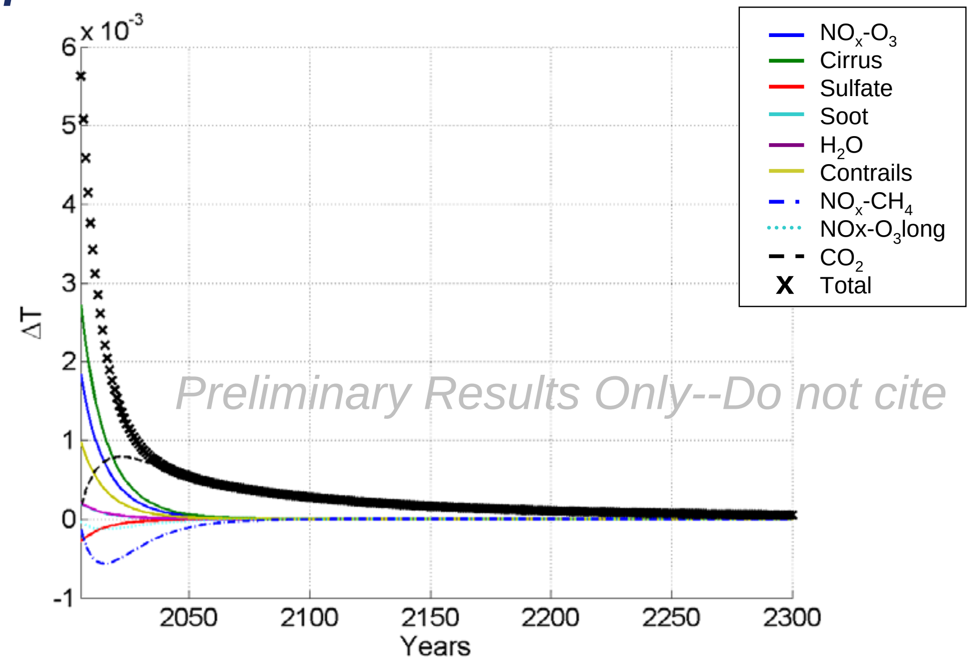
Treatment of uncertainty

- Sensitivity, Monte Carlo (MC), and Vary-all-but-one MC analyses
- Some uncertain parameters specified with uniform or triangular distributions
  - Emissions inventories (fixed here)
  - RF's for short-lived effects (Sausen, et al., 2005)
  - Climate sensitivities (Hansen, et al., 2005)
- Other uncertainties addressed with scenarios/choices/cases
  - IS92 background scenarios
  - FESG aviation scenarios
  - CO_2 response function choice
  - Temperature response function choice
  - Damage function choice
  - Discount rate choice
  - Distribution shape for uncertain parameters
  - Double uncertainty for all uncertain parameters

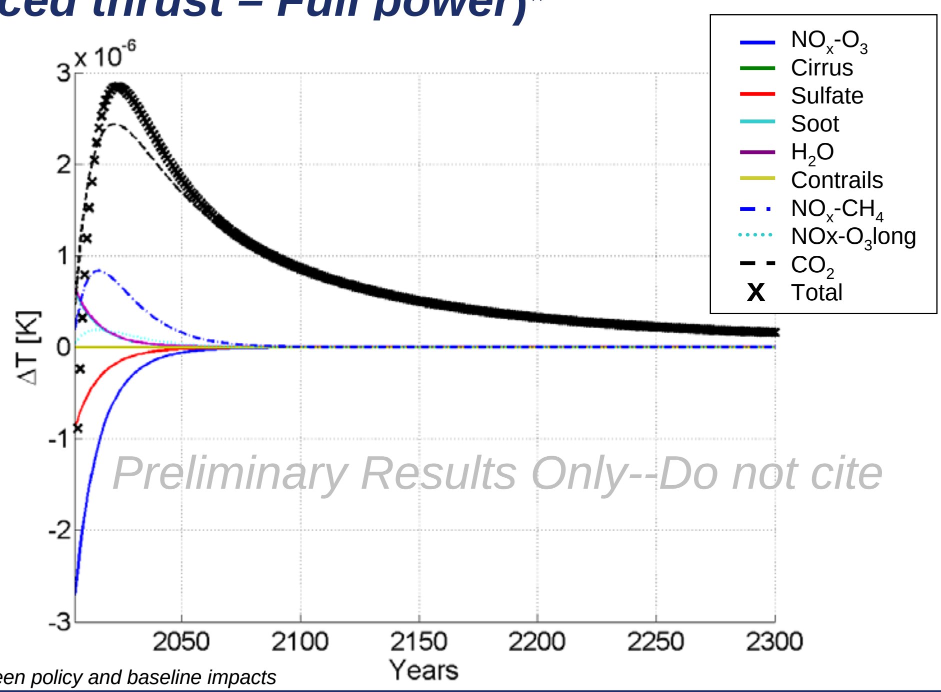
Baseline and policy definition

- **Background Emissions and GDP:**
  - IS92a +-4%, triangular distribution
- **Impulse Response**
  - Bern CC
  - Shine 2005, uniform distribution [λ = 1.5 to 4.5K]
- **Short-lived Radiative Forcings**
  - Sausen et al., 2005, triangular distribution
  - Stevenson et al., 2004 (methane, ozone)--discrete distribution
  - Reference ΔT, triangular distribution
- **Short-lived Efficacies set to 1**
- **Discount rate, r = 1, 3, 5%**
- **Damage function: Nordhaus and Boyer (2000)**
- **Policy definition: Reduced Thrust**
  - **+5% CO_2 and -1.6% NO_x below 10,000 feet relative to full thrust**
  - **Correspond to +0.31% CO_2 and -0.15% NO_x for global inventory**

Average Global Surface ΔT:
Full power

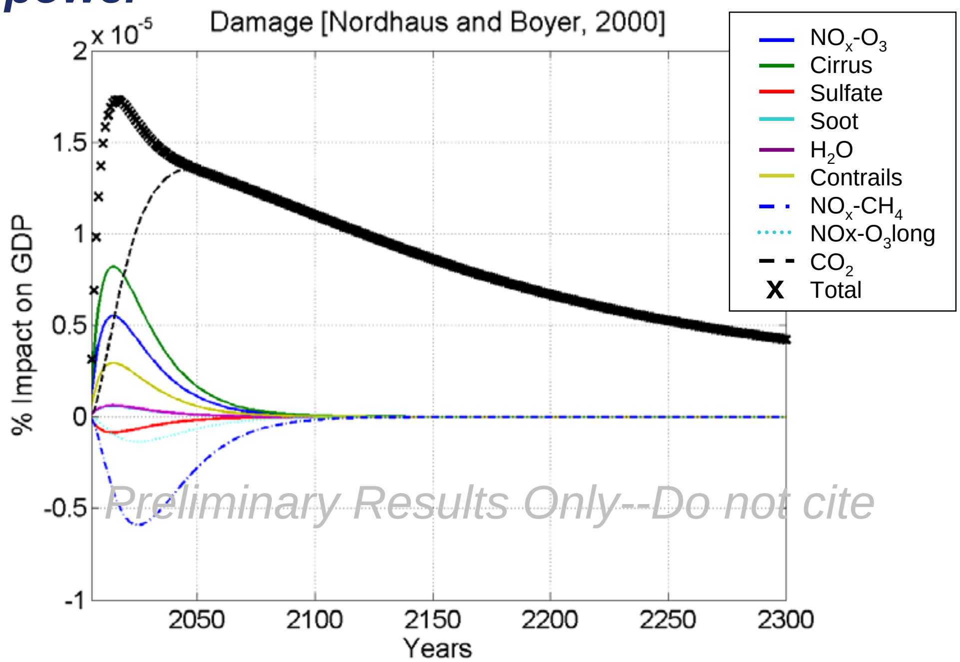


Change in Average Global Surface ΔT:
(*Reduced thrust – Full power*)*

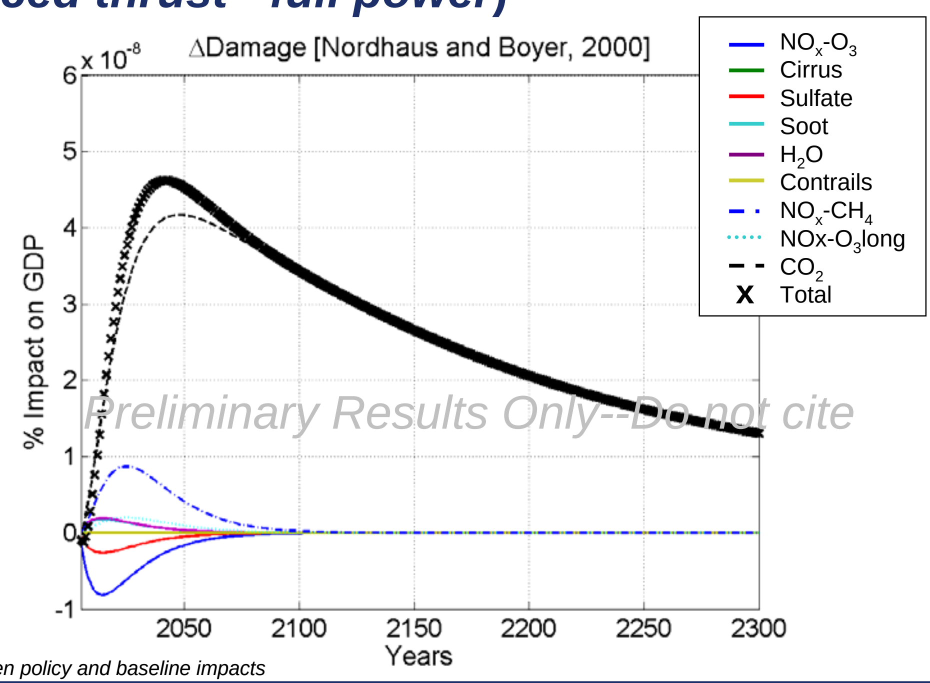


**Difference between policy and baseline impacts*

Damage [% GDP]:
Full power

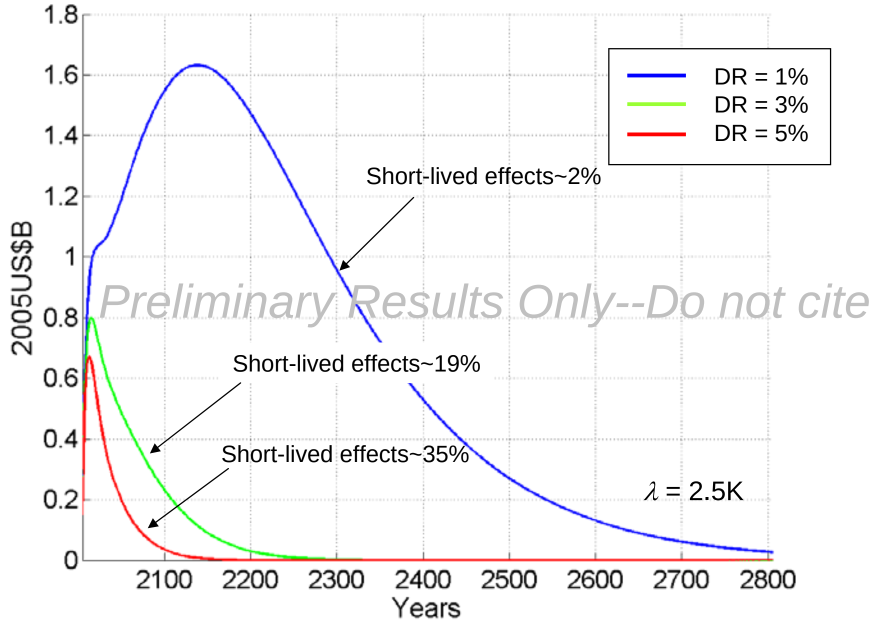


Change in Damage [% GDP]:
(*Reduced thrust - full power*)*

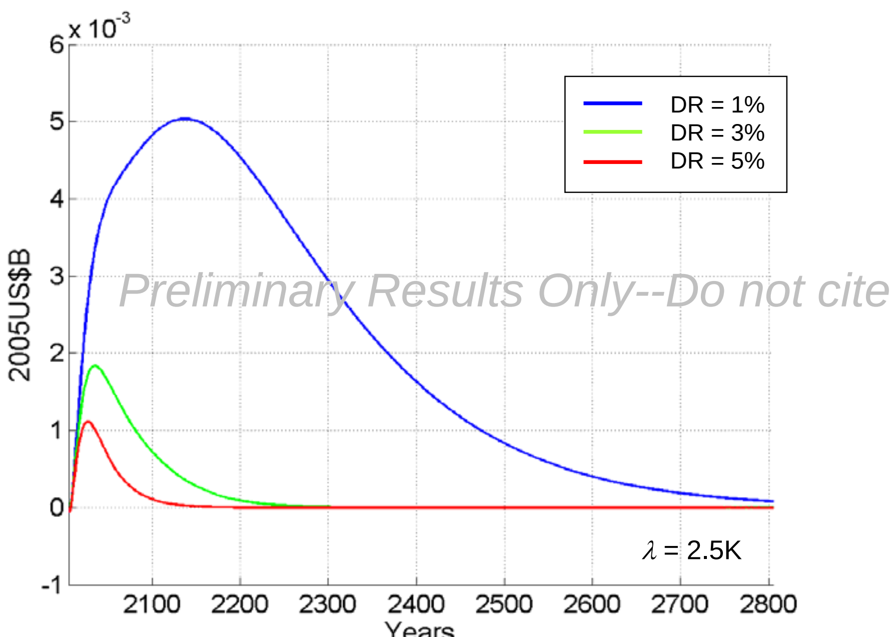


**Difference between policy and baseline impacts*

Impact of Discount Rate on Present Value: *Full power*

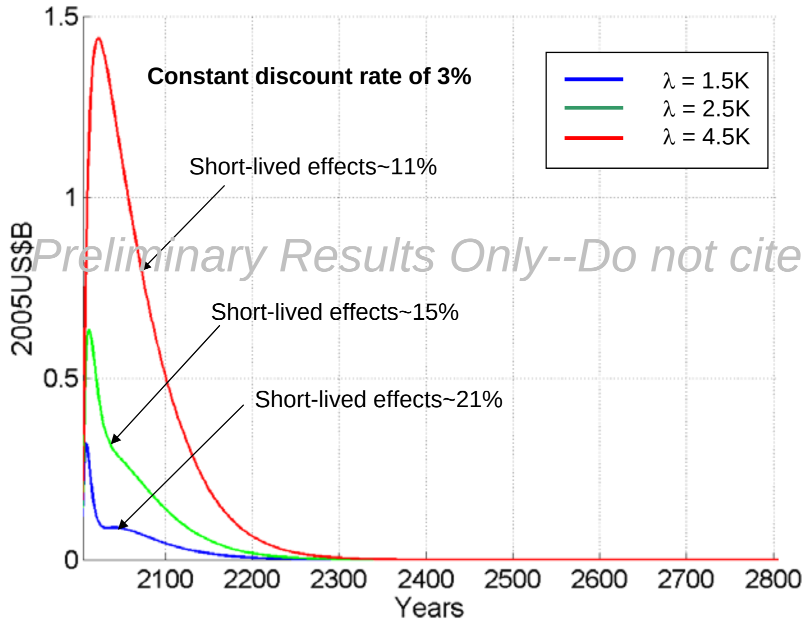


Impact of Discount Rate on Present Value: (*Reduced thrust - full power*)*

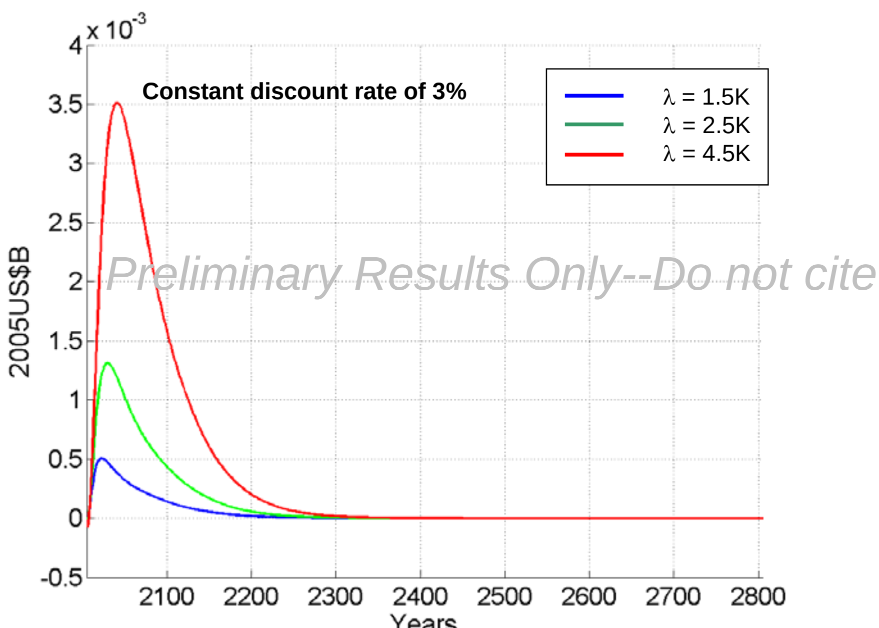


Difference between policy and baseline impacts

Impact of Climate Sensitivity on Present Value: *Full power*

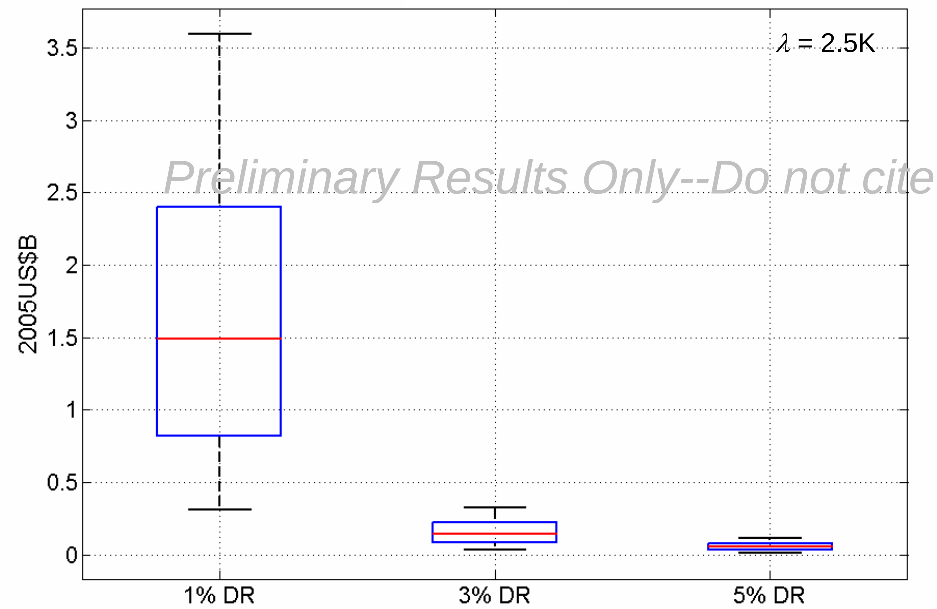


Impact of Climate Sensitivity on Present Value: (*Reduced thrust - full power*)*



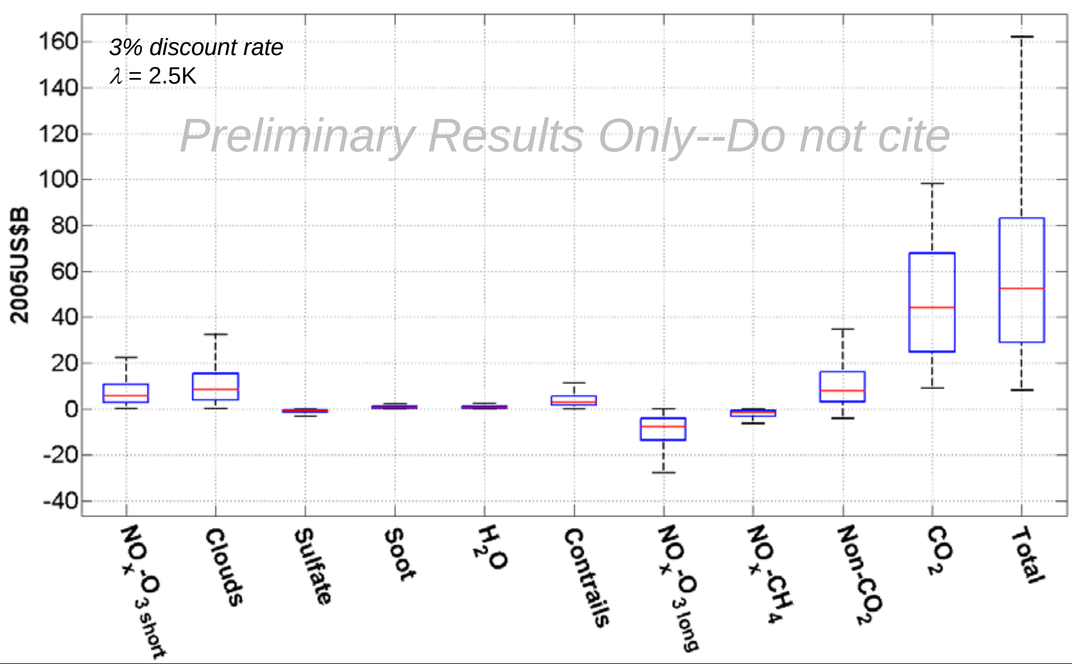
**Difference between policy and baseline impacts*

Impact of Discount Rate on NPV Change:
(*Reduced thrust - full power*)*

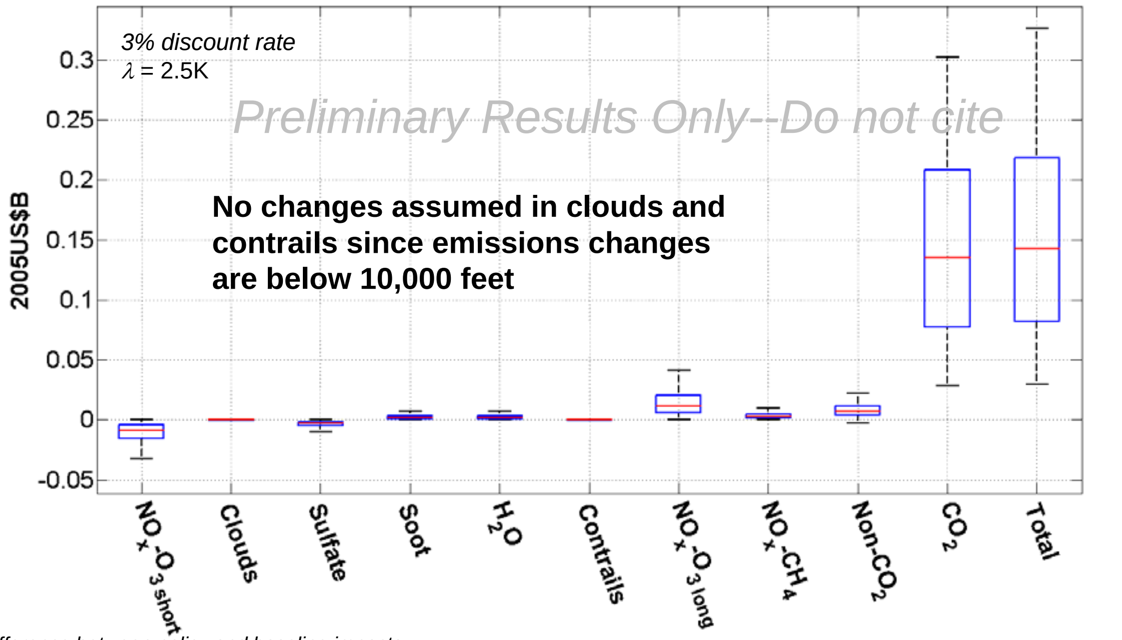


*Difference between policy and baseline impacts

NPV of Climate Impacts:
Full power

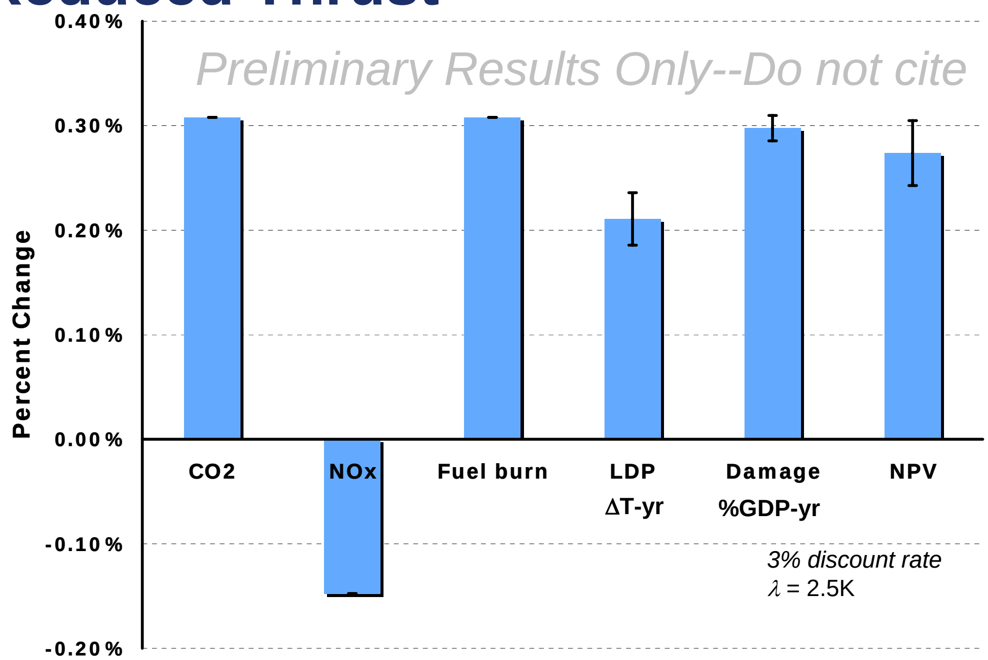


NPV of Climate Impacts:
(*Reduced thrust - full power*)*

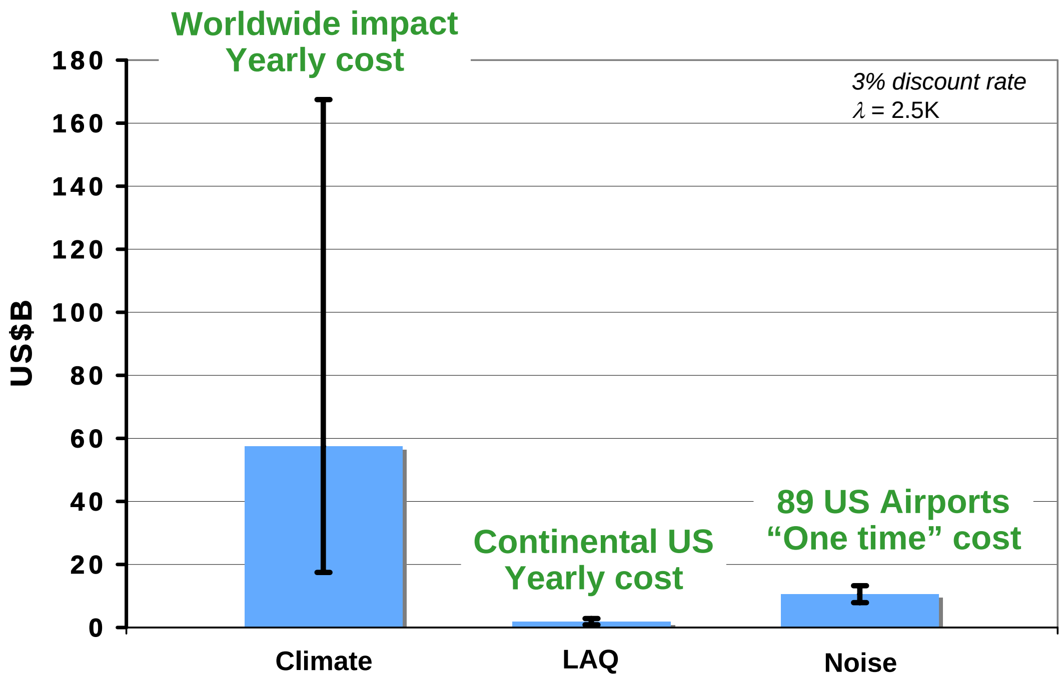


*Difference between policy and baseline impacts

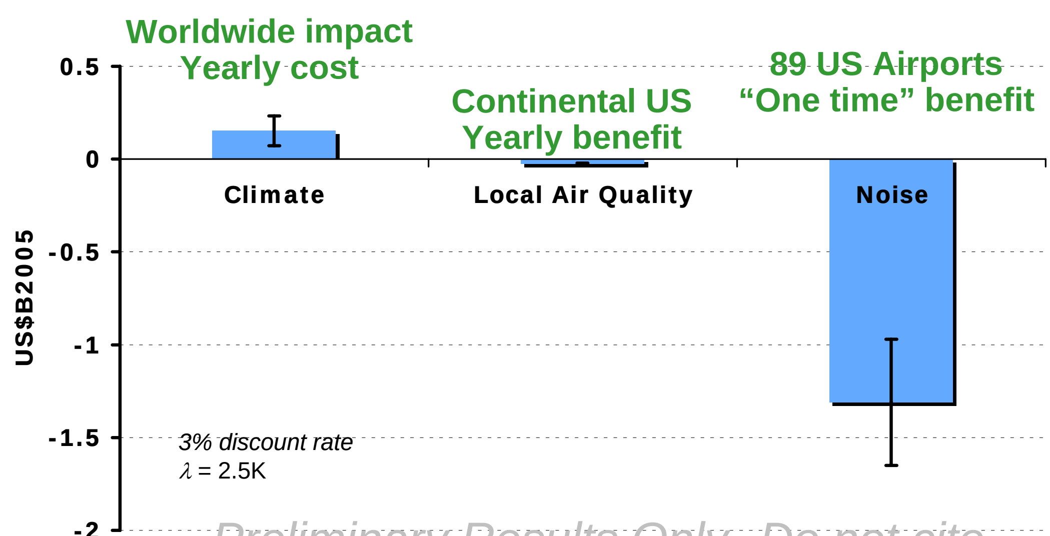
Summary of Climate Impact of Reduced Thrust



Interdependencies of baseline impact



Interdependencies of policy impact
(change due to reduced thrust relative to full thrust)



Preliminary Results Only--Do not cite

A word of caution

- These are NOT the "answers"
  - Apples-to-oranges comparisons
  - For a notional policy case
  - The numbers reflect a particular set of assumptions and scenarios
  - There may be errors
- These are examples of work in progress
  - Much work remains to assess and improve
  - And to better understand how to communicate and use such results

Summary of Reduced Thrust take-off

- Expanded upon previous ICAO/CAEP/WG2 Study… But
- Limited scope study
  - Single "representative" day
  - OAG operations only
  - System-wide 10% assumption
  - Exercised AEDT and BVB in APMT
- Reduction in noise impacts and local air quality impacts, with reduced thrust, but climate is negatively affected

Lessons and Next Steps

- **Lessons**
  - Sample problems valuable for identifying modeling gaps
  - As we begin to assess interdependencies many new metrics and perspectives
  - New metrics and perspectives may challenge conventional wisdom
  - New metrics and perspectives offer challenges and opportunities for policy-makers and those engaged in communicating risks to the general public
- **Next steps**
  - Evaluate and document results
  - Enhance tools based on lessons learned
- **APMT is a *Prototype***
  - Much work remains, results will change

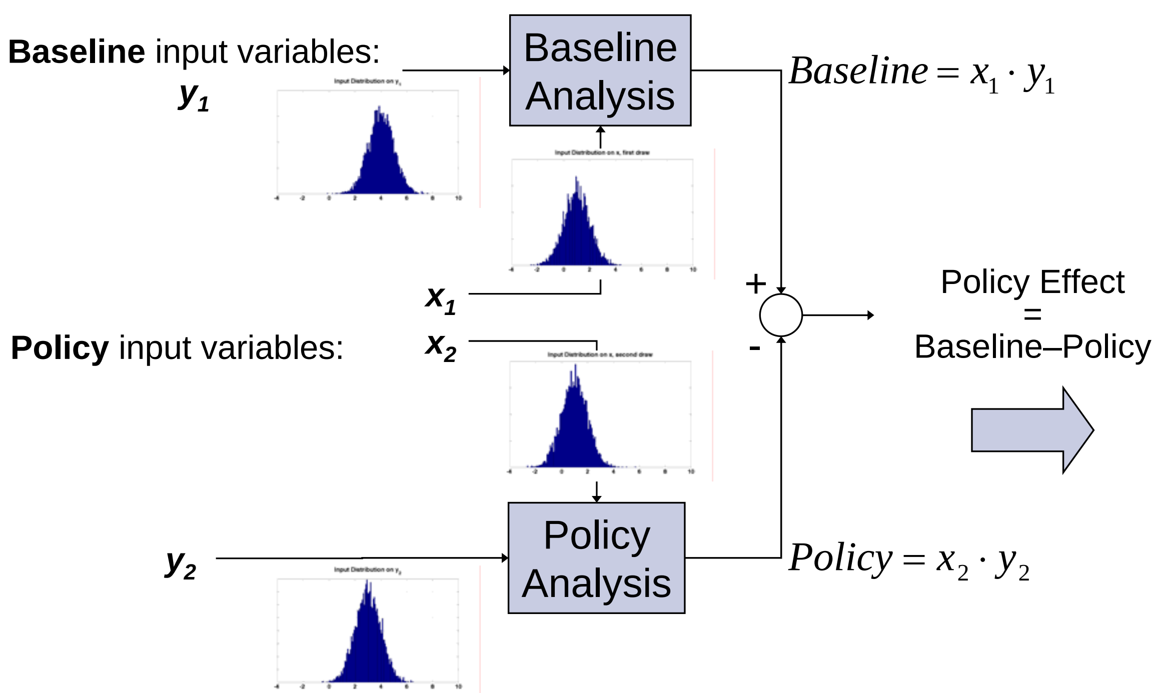
??? Questions ???

FAA Environmental Tools web site:

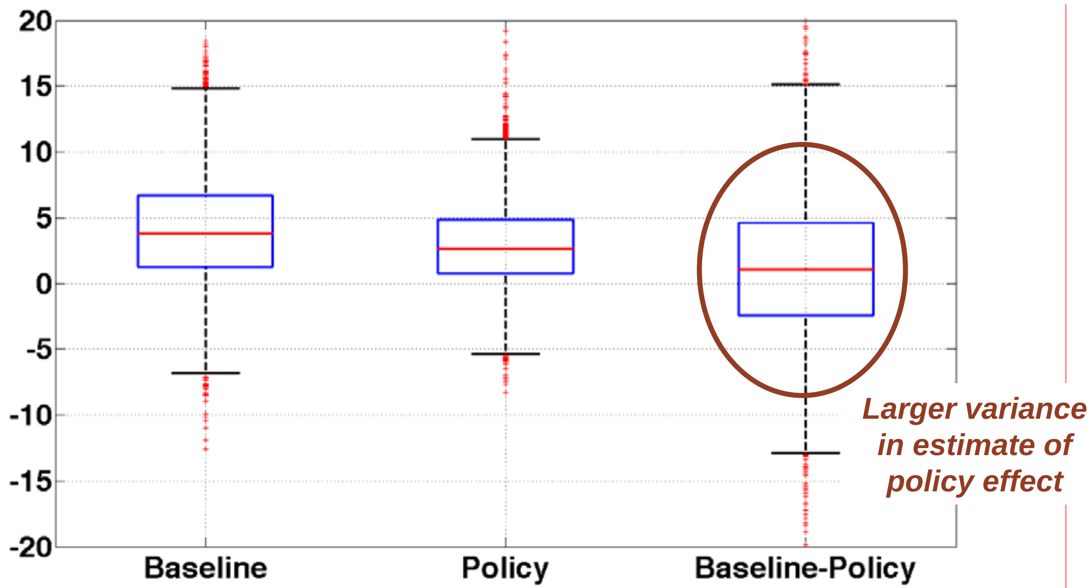
http://www.faa.gov/about/office_org/headquarters_offices/aep/models/

Appendix: statistical analysis example

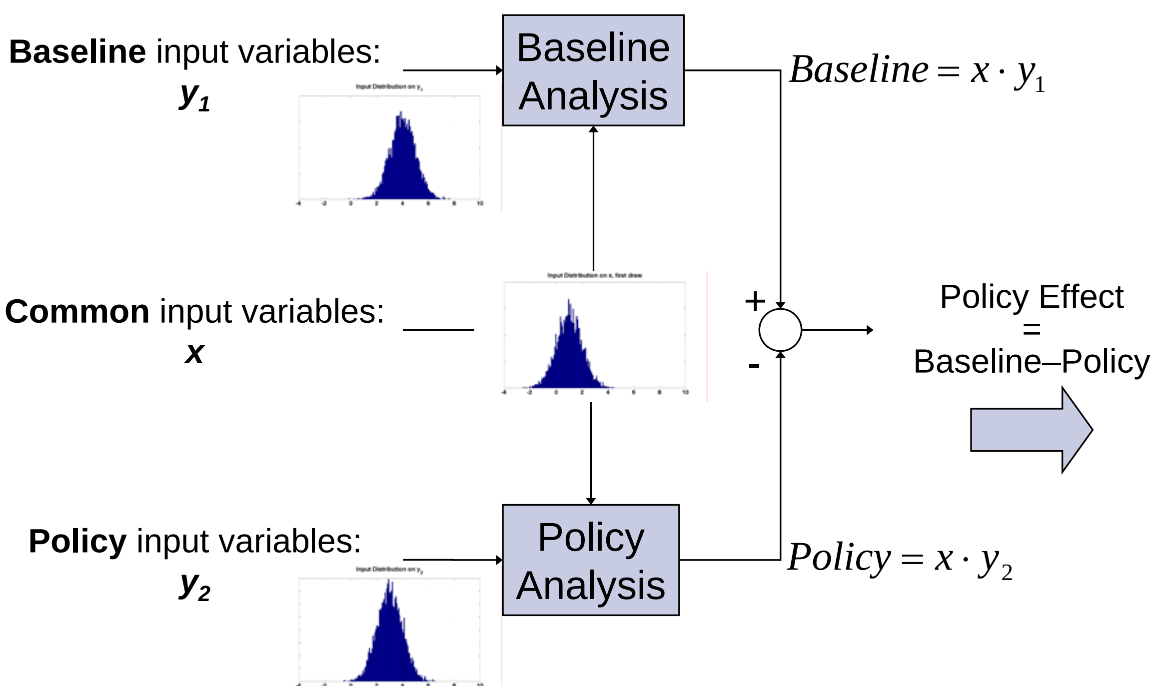
Statistics with independent parameters



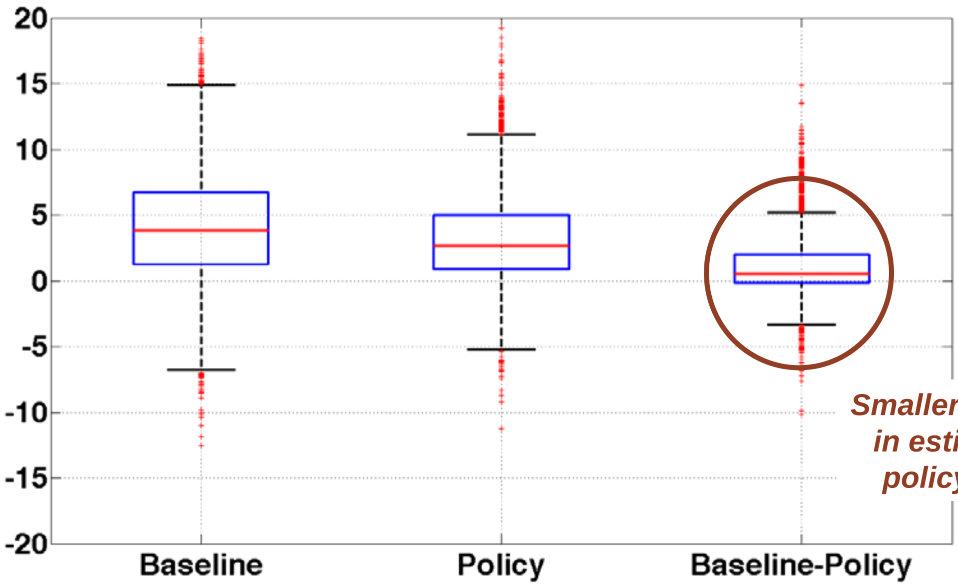
Estimate of policy effect– parameters independent for baseline and policy



Blocked statistical analysis example



Estimate of policy effect– some probabilistic parameters common



Smaller variance in estimate of policy effect