Compounding Benefits of Air Pollution Control
A Revised View of Air Pollution Economics

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Applying Epidemiology in Health Impact Assessment

Integrate risk estimates from epidemiological studies with air quality models to estimate

• The distribution of health impacts (affected populations), or
Applying Epidemiology in Health Impact Assessment

Integrate risk estimates from epidemiological studies with air quality models to estimate

- The distribution of health impacts (affected populations), or
- **Source attribution of health impacts (emissions responsible)**
Identifying Sources of Health Impacts

\[
\frac{\Delta $}{\Delta \text{Emissions}} = \frac{\Delta $}{\Delta \text{Mortality}} \times \frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}} \times \frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}
\]

Monetized benefits
Economics
Epidemiology
Air quality modeling

-- per-ton basis (benefits-per-ton or marginal benefit)
Traditional Linear CRF

\[
\ln(\text{HR}) = \beta C + \text{covariates}
\]
Linear vs Log-linear CRFs

\[
\ln(\text{HR}) = \beta \ln(C) + \text{covariates}
\]

\[
\ln(\text{HR}) = \beta C + \text{covariates}
\]
Traditional Health Impact Function

\[ M(\$) = M_0 \, \text{Pop}(1-e^{-\beta C})V_{SL} \]

- Mortality rate and population
- Derived from the CRF --- best model fit for O$_3$ and mortality in Canada
- Value of statistical life
Revised Health Impact Function

\[ M(C) = M_0 \, \text{Pop}(1 - e^{-\beta \ln C})V_{SL} \]

Mortality rate and population

Derived from the CRF

--- best fits for NO\textsubscript{2} and PM\textsubscript{2.5}
in Canada

Value of statistical life
Nonlinearity in Sensitivities

\[
\frac{\Delta \text{\$}}{\Delta \text{Emissions}} = \frac{\Delta \text{\$}}{\Delta \text{Mortality}} \times \frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}} \times \frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}
\]

- **Monetized benefits**
- Economics
- Epidemiology
- Air quality modeling

**Fields:**
- Economics
- Epidemiology
- Air quality modeling
Nonlinearity in Sensitivities

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\frac{\Delta \text{\$}}{\Delta \text{Emissions}} = \frac{\Delta \text{\$}}{\Delta \text{Mortality}} \times \frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}} \times \frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}
\]

- Monetized benefits
- Economics
- Epidemiology
- Air quality modeling
Adjoint Air Quality Modeling

Tracing mortality backwards to emissions: where influences come from (Pappin and Hakami, 2013).

\[ \Delta M(C) \]

\[ \Delta E_{x,y,t} \]

Inputs/ emissions

Outputs/ health impacts
Case Study

CMAQ-Adjoint
- May-Sept 2007
- 36 km resolution
- SAPRC99
Case Study

Cost Function, $J = \text{monetized non-accidental mortality in Canada attributable to}$
  - Long-term $O_3$ exposure
  - Long-term $NO_2$ exposure

Canadian Epidemiological Data (Crouse et al. EHP 2015)
  - $O_3 \beta = 0.0026 \text{ ppb}^{-1} \text{ (summertime average DM8A)}$
  - $NO_2 \beta = 0.0059 \text{ ppb}^{-1} \text{ (summertime average)}$
  - $NO_2 \text{ log-linear } \beta = 0.0732 \text{ (---note difficulty interpreting)}$
Findings: $O_3$ Mortality

- Linear CRF
- Non-linear atmospheric response
Benefits-per-ton of NO\textsubscript{x} Control

O\textsubscript{3}, At 2007 Emission Levels
Benefits-per-ton of NO\textsubscript{x} Control
\textit{O}\textsubscript{3}, At 50% Emissions Abatement
Benefits-per-ton of NO$_x$ Control O$_3$, At 85% Emissions Abatement
Nonlinear Behavior by Source

Graph showing the relationship between emissions abatement and benefit-per-ton for Toronto, Montreal, Vancouver, and Ottawa. The graph illustrates how the benefit-per-ton increases as emissions abatement increases, with different curves for each city.
Similar Behavior in the U.S.
(Pappin et al. ES&T 2015)
Conclusions - 1

- Non-linearity in $O_3$ based benefits are due entirely to atmospheric chemistry
- This becomes increasingly important as we move towards lower pollution levels
Findings: NO$_2$ Mortality

- Linear vs log-linear CRFs
Traditional, Linear CRF
Benefits-per-ton of NO$_x$ Control

NO$_2$, At 2007 Emission Levels
Benefits-per-ton of NO$_x$ Control
NO$_2$, At 85% Emissions Abatement
Log-linear CRF
Benefits-per-ton of NO\textsubscript{x} Control
NO\textsubscript{2}, At 2007 Emission Levels
equal slopes at ~11 ppb
Benefits-per-ton of NO\textsubscript{x} Control

NO\textsubscript{2}, At 50% Emissions Abatement
Benefits-per-ton of NO\textsubscript{x} Control
NO\textsubscript{2}, At 85% Emissions Abatement
Linear vs Log-linear
\( \text{NO}_2 \), At 2007 Emission Levels
Linear vs Log-linear
NO₂, At 85% Emissions Abatement

-- note increasing scale
Conclusions - 2

- Important differences between linear and log-linear CRFs for NO$_2$, particularly in cleaner environments
- Benefits are larger for NO$_2$ than O$_3$
Policy Relevance
emission abatement

monetary value ($/ton)

0% 100%

A

A^* new

Pappin et al. ES&T 2015
Considerations for PM

- Indications of atmospheric nonlinearity for PM$_{2.5}$ exist in the literature (Fann et al. 2012; Holt et al. 2015; Hakami et al. 2003; Zhang et al. 2012)
- Combined with a potentially non-linear CRF, benefits-per-ton for PM$_{2.5}$ may increase substantially towards lower pollution levels
- Further research using a multiphase adjoint model can shed light on this
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Limitations

• Constant mortality rates assumed over time
• Long-term benefits (i.e., chronic exposure mortality) modeled in a short, 5-month simulation episode
• Uncertainty in atmospheric modeling, CRFs, and economic valuation lead to uncertainties in benefit-per-ton estimates
Canadian Census, Environment, and Health Cohort (CanCHEC)

- 2.6 million subjects > 25 years of age
- $O_3$, $NO_2$, $PM_{2.5}$ and mortality analyzed (various causes-of-death)
- Log-linear models appropriate for $NO_2$ and $PM_{2.5}$
- Linear model most appropriate for $O_3$
CanCHEC O$_3$ and NO$_2$ CRFs

Non-accidental mortality

- **Linear**: $\ln(HR) = 0.0027C_{O3} + 0.0059C_{NO2} + $ covariates

- **Log-linear**: $\ln(HR) = 0.0026C_{O3} + 0.0599\ln(C_{NO2}+1) + $ covariates
Linear and Log-linear NO$_2$ CRFs

Analysis of CanCHEC

\[ \ln(\text{HR}) = 0.0026C_{O_3} + 0.0599\ln C_{\text{NO}_2} \]

\[ \ln(\text{HR}) = 0.0027C_{O_3} + 0.0059C_{\text{NO}_2} \]
Identifying Sources of Health Impacts

A question of sensitivity analysis

\[
\frac{\Delta \text{Mortality}}{\Delta \text{Emissions}} = \frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}} \times \frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}
\]

Epidemiology

Air quality modeling