Optimization of Multipollutant Air Quality Management Strategies

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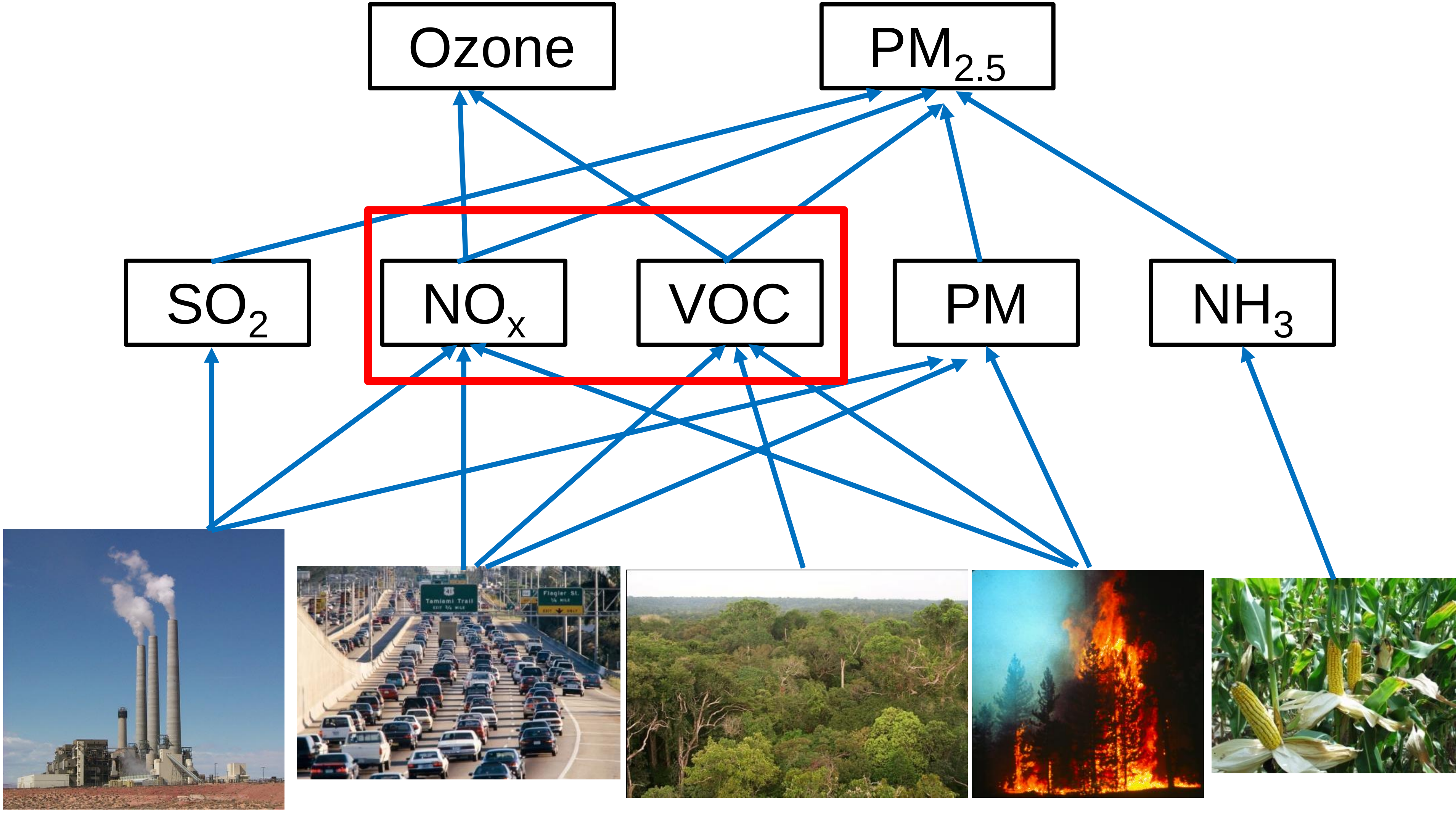
Emission Sources of Ozone and $PM_{2.5}$ Precursors



Ozone

$PM_{2.5}$

SO_2

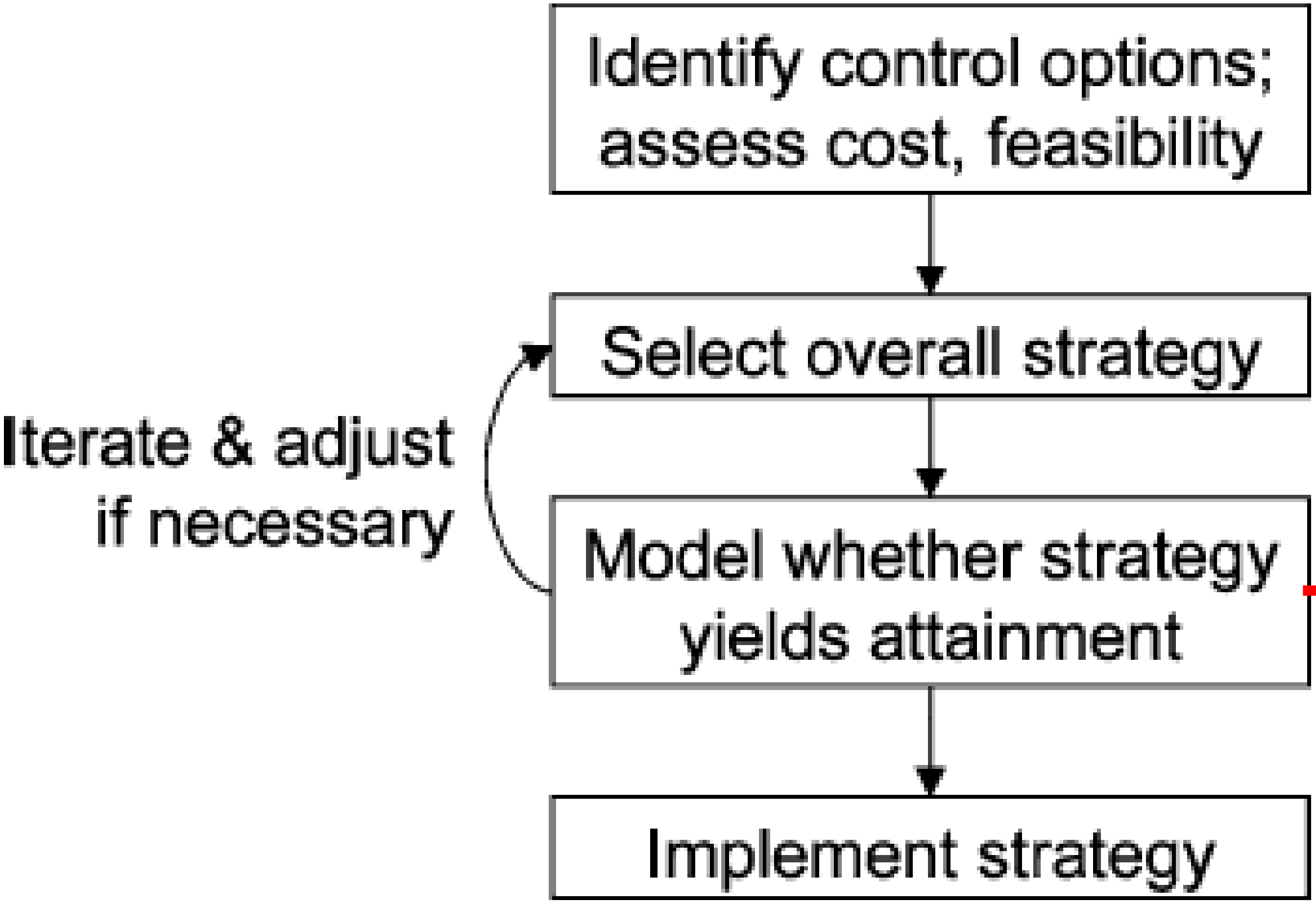
NO_x

VOC

PM

NH_3

Traditional Framework for Developing State Implementation Plan (SIP)



Identify control options; assess cost, feasibility

Select overall strategy

Model whether strategy yields attainment

Implement strategy

Iterate & adjust if necessary

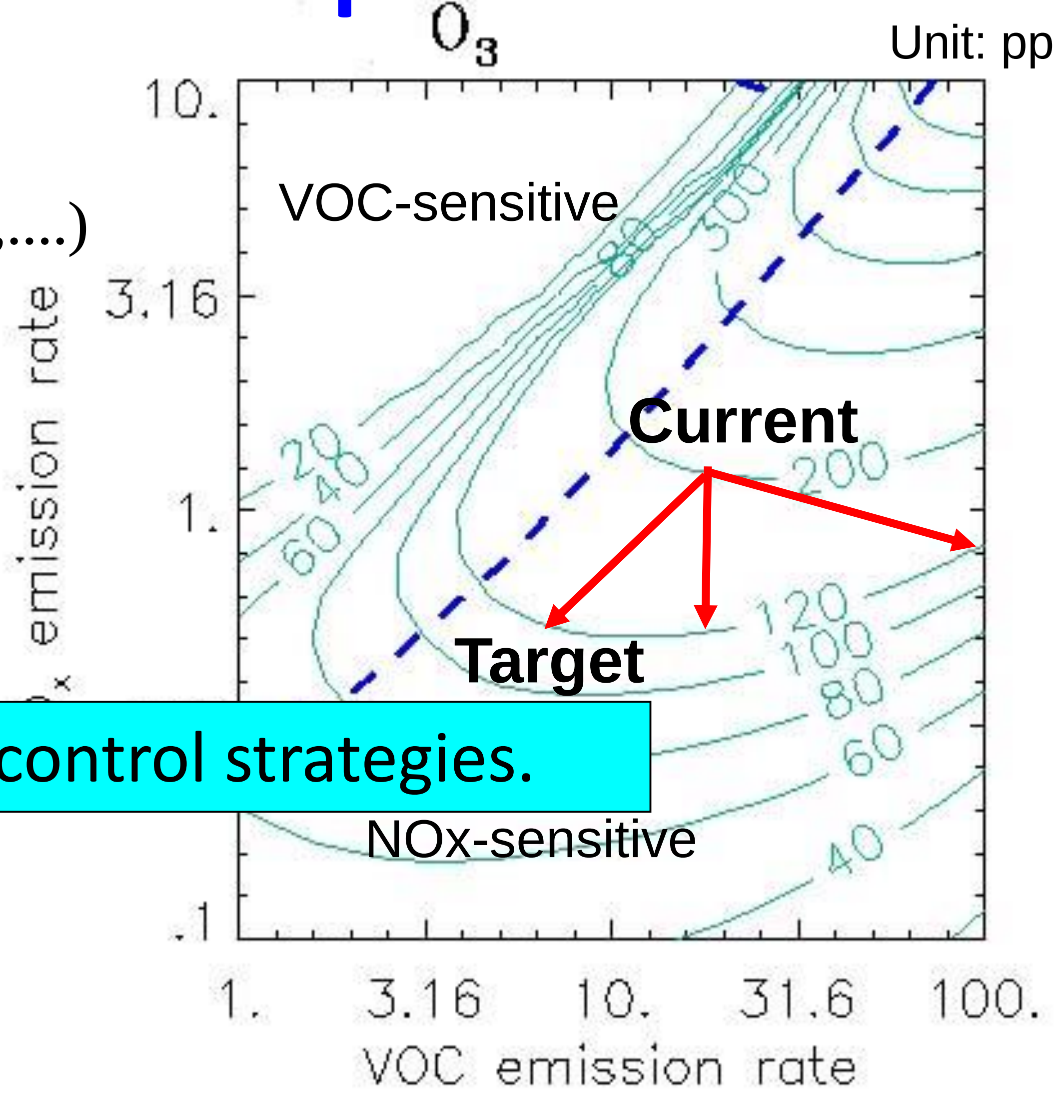
Air Quality Modeling

Cohan et al., 2007

Ozone Isopleths

$$[O_3] = f(NOx, VOC, met., ...)$$

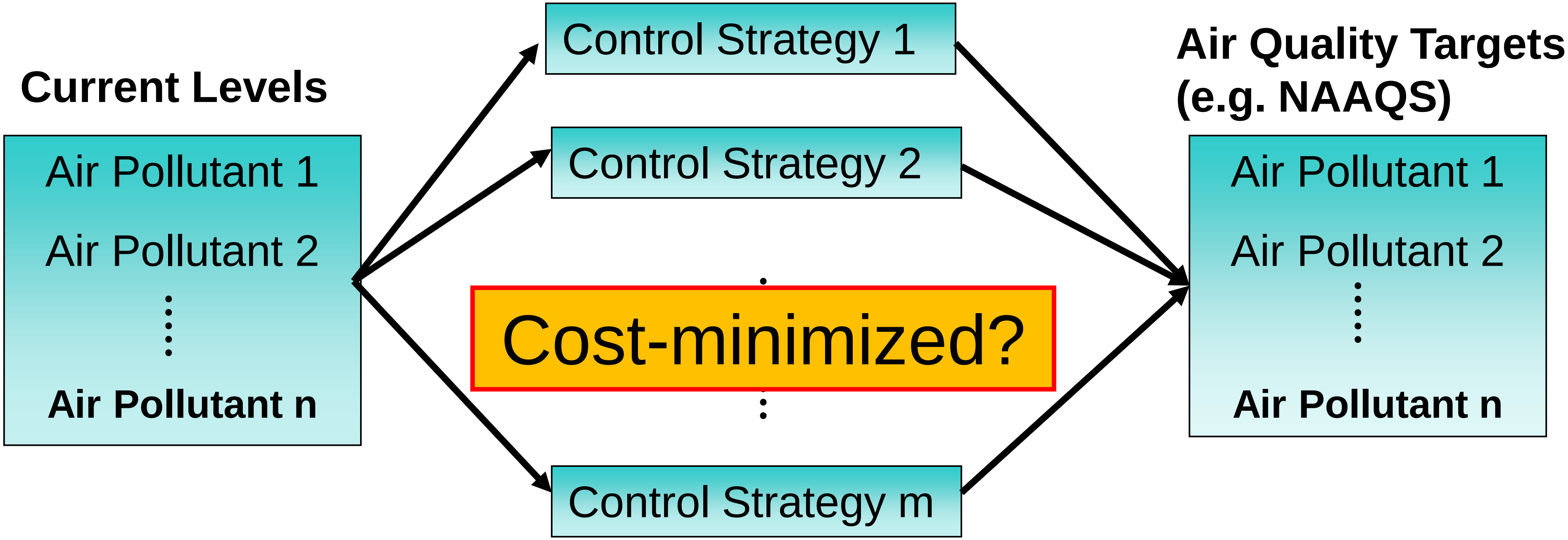
Unit: ppb



Multiple choices for control strategies.

http://www-personal.umich.edu/~sillman/ozone.htm

Air Pollution Control Strategies for Multi-Pollutants and Multi-Locations



Current Levels

Air Pollutant 1

Air Pollutant 2

⋮

Air Pollutant n

Control Strategy 1

Control Strategy 2

⋮

Cost-minimized?

⋮

Control Strategy m

Air Quality Targets (e.g. NAAQS)

Air Pollutant 1

Air Pollutant 2

⋮

Air Pollutant n

Challenge:

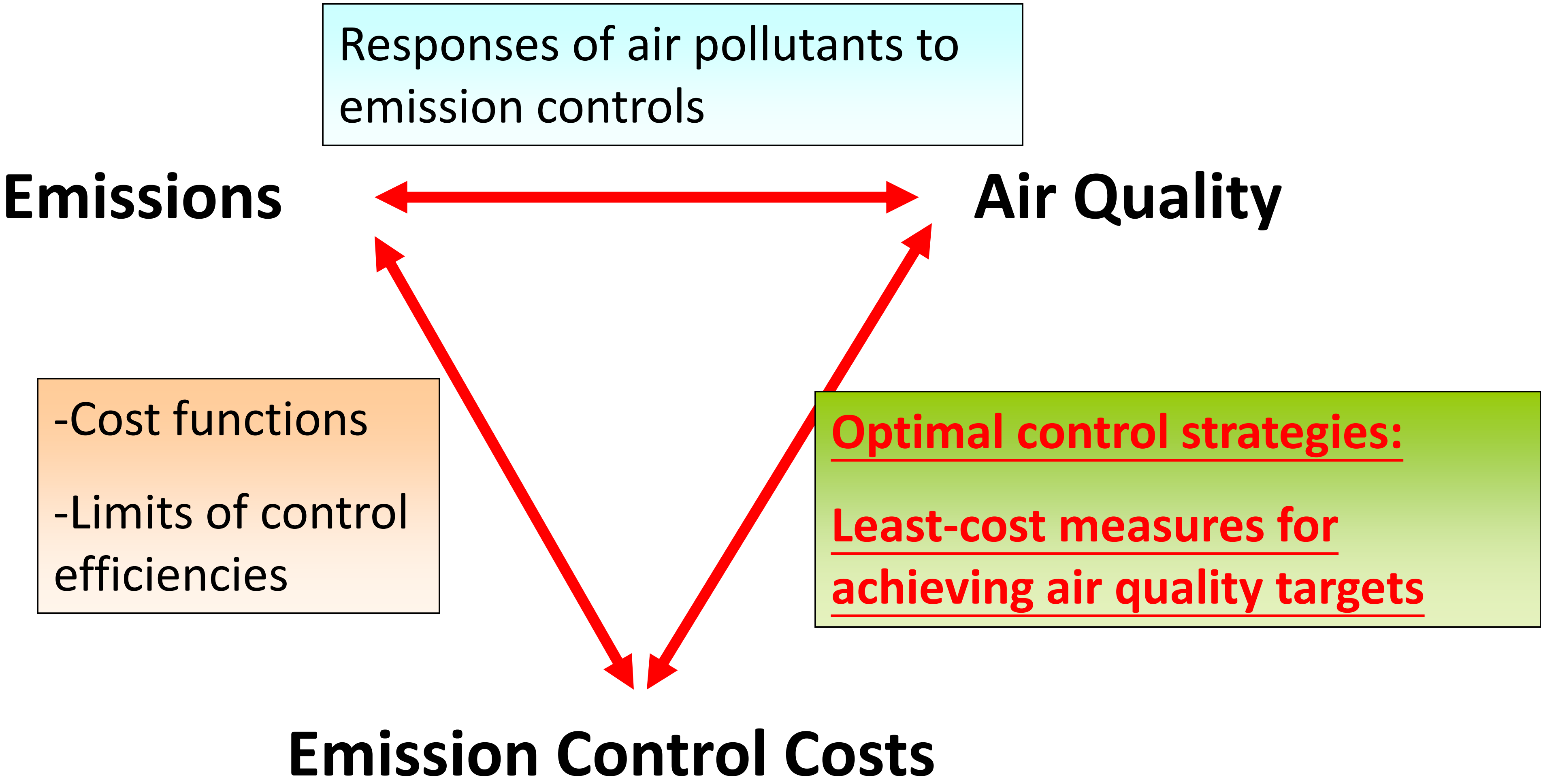
Air pollutants at different locations have different responses to changes in precursor emissions from common sources

Objective -I

Development of optimal (i.e., least-cost) control strategies (**OPtimal Integrated Emission Reduction Alternatives (OPERA)**) for:

- achieving multipollutant air quality targets
- at multiple locations simultaneously

What We Need to Develop Optimized Air Quality Control Strategies?



Responses of air pollutants to emission controls

Emissions

Air Quality

-Cost functions

-Limits of control efficiencies

Optimal control strategies:

Least-cost measures for achieving air quality targets

Emission Control Costs

Case Study – Air Quality for NE U.S.

- EPA Models3:
  - MM5
  - SMOKE
  - CMAQ-HDDM

-Two pollutants:
  - ozone (target: 75ppb)
  - $PM_{2.5}$ (target: 25 µg/m^3)

-Regional precursors:
  - SO_2
  - NO*x*
  - VOC

- Local primary $PM_{2.5}$

Four regions

Ozone Sensitivities (CMAQ-HDDM)

Unit: ppb

		Atlanta	Chicago	D.C.	New York	Philadelphia
Region	**Sensitivity/MDA8h O_3**	**84.8**	**61.7**	**85.6**	**91.8**	**84.4**
OTR	1st NOx	12.20	0.22	55.30	-14.20	26.10
	1st VOC	0.04	0.04	-0.32	16.20	5.00
	2nd NOx	-11.60	-0.07	-39.70	-22.50	-50.20
	2nd VOC	-0.88	-0.01	-0.42	0.55	-1.53
	2nd NOx_VOC	2.40	0.01	2.60	-1.03	6.70
LADCO	1st NOx	0.42	5.20	0.52	-0.02	0.72
	1st VOC	0.09	3.60	-0.06	0.02	-0.02
	2nd NOx	-0.11	-19.80	-0.08	0.02	-0.09
	2nd VOC	-0.02	-0.59	~ 0	~ 0	~ 0
	2nd NOx_VOC	0.06	2.30	0.01	~ 0	0.01
CENRAP	1st NOx	0.16	0.57	0.30	0.01	0.33
	1st VOC	0.01	0.01	-0.01	~ 0	0.01
	2nd NOx	-0.03	-0.07	-0.04	~ 0	-0.04
	2nd VOC	~ 0	~ 0	~ 0	~ 0	~ 0
	2nd NOx_VOC	0.01	0.01	0.01	~ 0	0.01
SEMAP	1st NOx	26.80	0.02	0.09	~ 0	~ 0
	1st VOC	1.39	0.01	~ 0	~ 0	~ 0
	2nd NOx	-32.90	-0.01	-0.01	~ 0	~ 0
	2nd VOC	-0.19	~ 0	~ 0	~ 0	~ 0
	2nd NOx_VOC	1.89	~ 0	~ 0	~ 0	~ 0

Sensitivities of $PM_{2.5}$ (CMAQ-HDDM) and Primary $PM_{2.5}$ Concentrations

Unit: μg/m^3

		Atlanta	**Chicago**	**D.C.**	**New York**	**Philadelphia**
Region	Sensitivity/$PM_{2.5}$	16.10	26.25	11.73	38.83	30.76
OTR	1st NOx	0.23	0.05	1.54	5.00	8.81
	1st VOC	-0.02	-0.03	-0.22	0.17	-0.48
	2nd NOx	-0.14	-0.02	-0.50	-1.29	-1.56
	2nd VOC	0.01	~ 0	0.04	~ 0	0.06
	2nd NOx_VOC	~ 0	~ 0	-0.03	0.04	-0.02
	1st SO_2	0.67	0.12	1.65	1.25	2.82
LADCO	1st NOx	~ 0	2.31	0.02	0.06	0.24
	1st VOC	~ 0	-0.40	-0.01	-0.01	-0.06
	2nd NOx	0.01	-1.63	-0.01	-0.01	-0.04
	2nd VOC	~ 0	0.04	~ 0	~ 0	~ 0
	2nd NOx_VOC	~ 0	0.03	~ 0	~ 0	~ 0
	1st SO_2	0.16	2.96	0.07	0.04	0.12
CENRAP	1st NOx	~ 0	0.25	0.01	0.02	0.11
	1st VOC	~ 0	-0.02	~ 0	~ 0	-0.01
	2nd NOx	~ 0	-0.03	~ 0	~ 0	-0.02
	2nd VOC	~ 0	~ 0	~ 0	~ 0	~ 0
	2nd NOx_VOC	~ 0	~ 0	~ 0	~ 0	~ 0
	1st SO_2	0.04	0.27	0.01	0.01	0.02
SEMAP	1st NOx	0.63	0.01	~ 0	~ 0	~ 0
	1st VOC	-0.01	~ 0	~ 0	~ 0	~ 0
	2nd NOx	0.11	~ 0	~ 0	~ 0	~ 0
	2nd VOC	~ 0	~ 0	~ 0	~ 0	~ 0
	2nd NOx_VOC	-0.01	~ 0	~ 0	~ 0	~ 0
	1st SO_2	0.77	0.03	0.03	~ 0	0.01
Primary $PM_{2.5}$		3.83	9.1	3.57	10.52	7.08

August 2, 2007

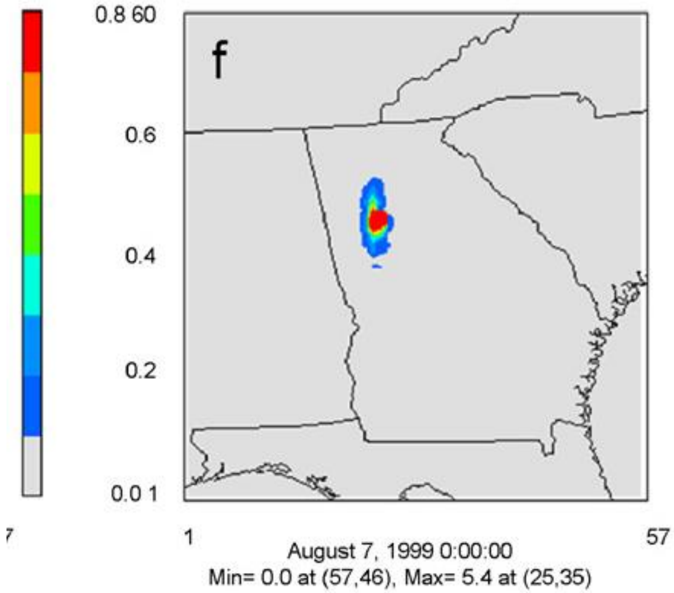
Assumptions

1. First-order sensitivities:

$$C_{i,new} \approx C_{i,\ prior} + \Delta\varepsilon_j S_{i,j} + H.O.T \quad \Rightarrow \quad S_{i,j} \approx \frac{\partial C_i}{\partial \varepsilon_j}$$

2. Ignore co-benefits of emission reductions for multiple precursors

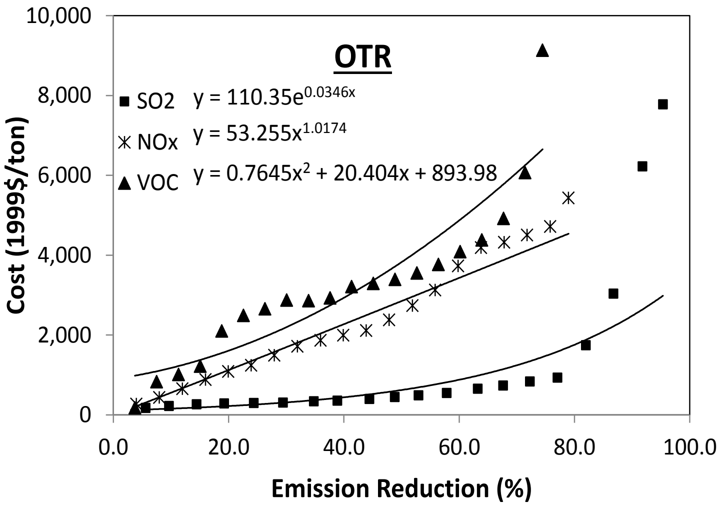
3. Primary $PM_{2.5}$ emissions only have local effects on air quality: Metropolitan Statistical Area (MSA)

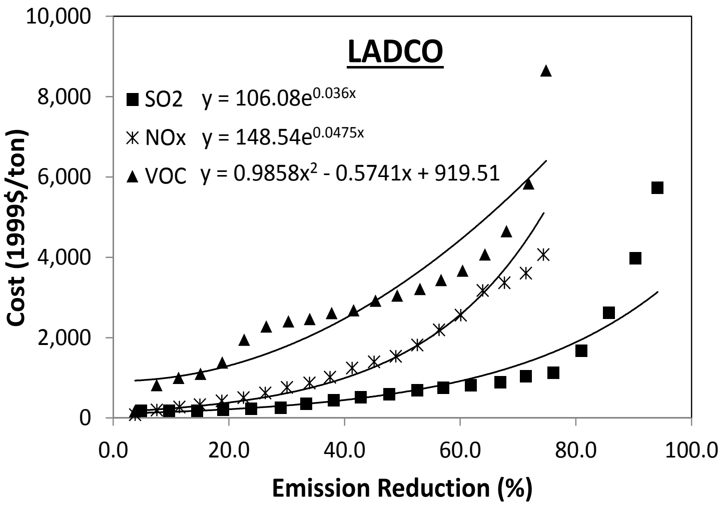


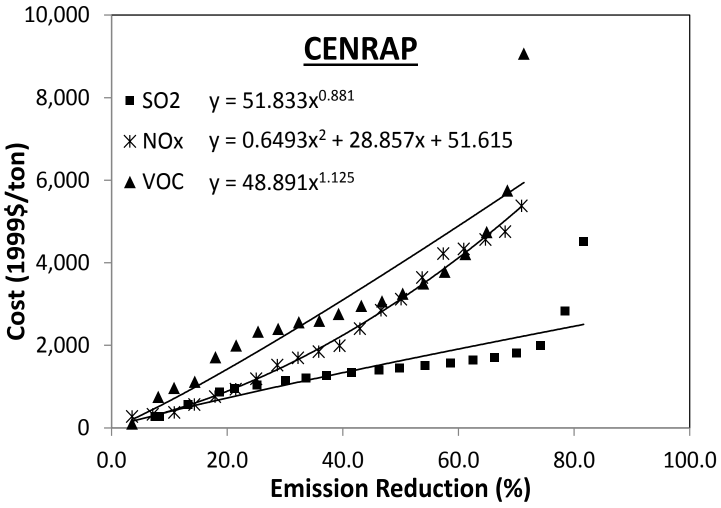
Cost Analysis Software-AirControlNET

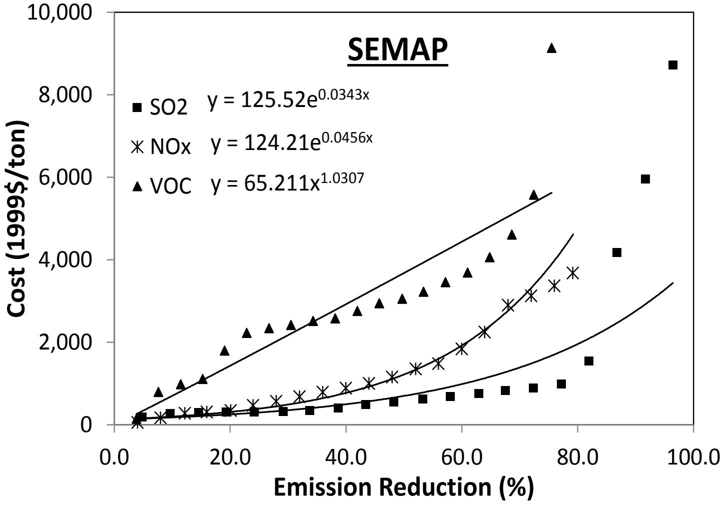
- US EPA’s emission control analysis tool
- Provide the information of mass of emission reduced and associated annualized costs
- $Cost_{i,j}(\Delta E_{i,j})$, $\Delta E_{i,j}$ is the amount of emission reductions of species i from region j
- Costs of reductions in anthropogenic precursor emissions do not increase linearly
- Higher ratios of emission reductions are expected to be more expensive

Per-ton Cost of Emission Reduction
(EPA AirControlNET)

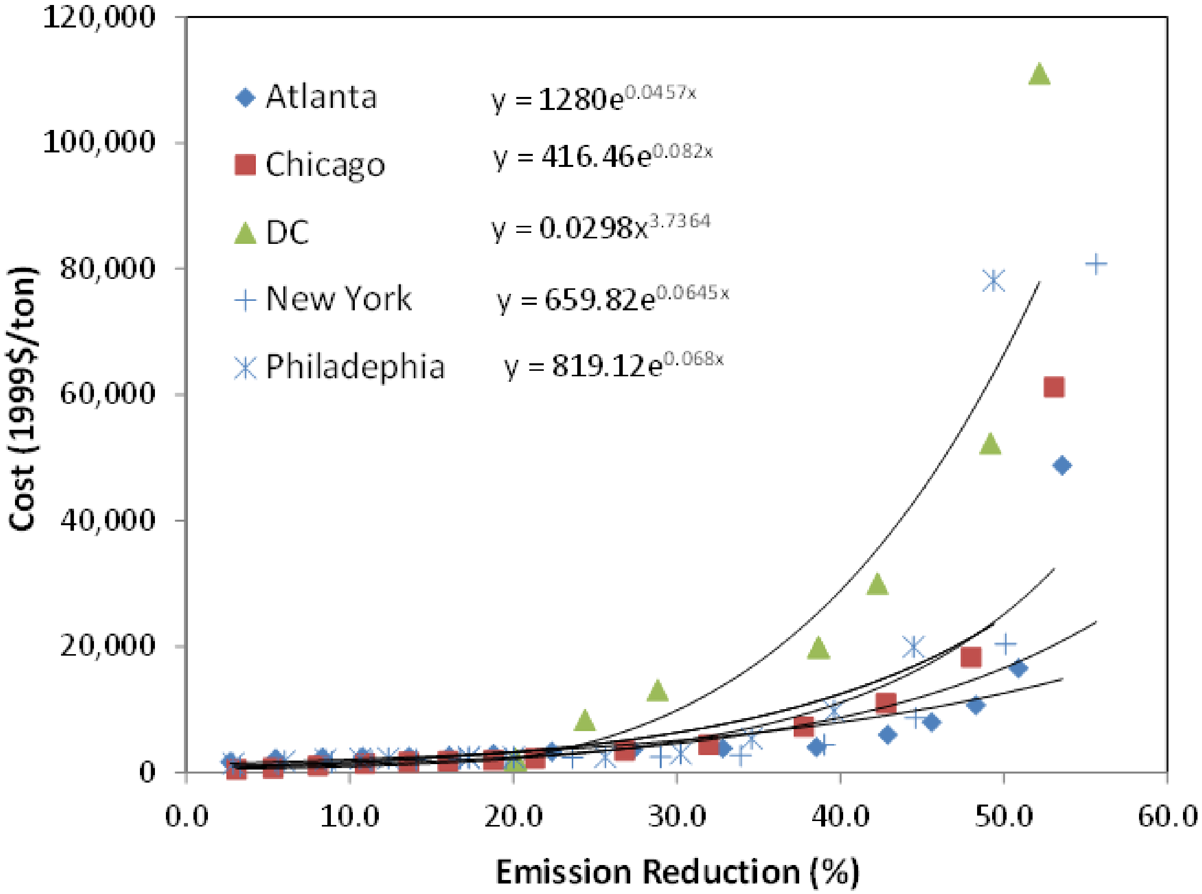








Per-ton Cost of Local Primary $PM_{2.5}$ Emission Reductions (EPA AirControlNET)



OPERA –I Formulation

Minimize $\sum_{i,j} Cost_{i,j}\left(\Delta\varepsilon_{i,j}\right) + \sum_{k} Cost_{primary\_PM\,2.5,k}\left(\Delta\varepsilon_{primary\_PM\,2.5,k}\right)$

Subject to:

Ozone target

$$\sum_{i,j} \Delta\varepsilon_{i,j}\, S_{O_3,\, i,\, j,k} \geq C_{O_3,\, prior,k} - \underline{C_{O_3,\, target,k}}$$

PM$_{2.5}$ target

$$\sum_{i,j} \Delta\varepsilon_{i,j}\, S_{PM_{2.5},i,j,k} + \Delta\varepsilon_{primary\_PM_{2.5},k} C_{primary\_PM_{2.5},k} \geq C_{PM_{2.5},prior,k} - \underline{C_{PM_{2.5},target,k}}$$

$$\left(\begin{array}{l}
0 \leq \Delta\varepsilon_{SO_2,\, j} \leq R_{SO_2,\, j} \\
0 \leq \Delta\varepsilon_{NOx,\, j} \leq R_{NOx,\, j} \\
0 \leq \Delta\varepsilon_{VOC,\, j} \leq R_{VOC,\, j} \\
0 \leq \Delta\varepsilon_{primary\_PM_{2.5},k} \leq R_{primary\_PM_{2.5},k}
\end{array}\right)$$

Constraints for emission control efficiencies

Results of Case Study

Target - ozone: 75ppb and PM$_{2.5}$: 25 μg/m^3

	Atlanta	Chicago	D.C.	New York	Philadelphia	Four Cities[2]
Reduction (%) in controllable SO$_2$ emissions						
OTR	~ 0	~ 0	~ 0	infeasible	~ 0	~ 0
LADCO	~ 0	~ 0	~ 0	infeasible	~ 0	~ 0
CENRAP	~ 0	~ 0	~ 0	Infeasible	~ 0	~ 0
SEMAP	~ 0	~ 0	~ 0	Infeasible	~ 0	~ 0
Reduction (%) in controllable NO$_x$ emissions						
OTR	15.8	~ 0	20.7	Infeasible	41.6	41.9
LADCO	1.6	0.3	0.8	infeasible	7.9	8.0
CENRAP	0.8	~ 0	0.5	Infeasible	5.3	5.4
SEMAP	38.9	~ 0	~ 0	Infeasible	~ 0	22.9
Reduction (%) in controllable VOC emissions						
OTR	0.5	~ 0	~ 0	Infeasible	37.5	37.2
LADCO	~ 0	~ 0	~ 0	Infeasible	~ 0	~ 0
CENRAP	~ 0	~ 0	~ 0	Infeasible	~ 0	~ 0
SEMAP	3.4	~ 0	~ 0	infeasible	~ 0	0.7
Reduction (%) in primary PM$_{2.5}$ emissions						
Atlanta	~ 0	~ 0	~ 0	Infeasible	~ 0	~ 0
Chicago	~ 0	13.9	~ 0	Infeasible	~ 0	11.5
D.C.	~ 0	~ 0	~ 0	Infeasible	~ 0	~ 0
New York	~ 0	~ 0	~ 0	infeasible	~ 0	~ 0
Philadelphia	~ 0	~ 0	~ 0	Infeasible	34.2	33.8
Cost (millions of 1999$)	**1,333**	**253**	**838**	**-**	**5,639**	**5,831**

Conclusions

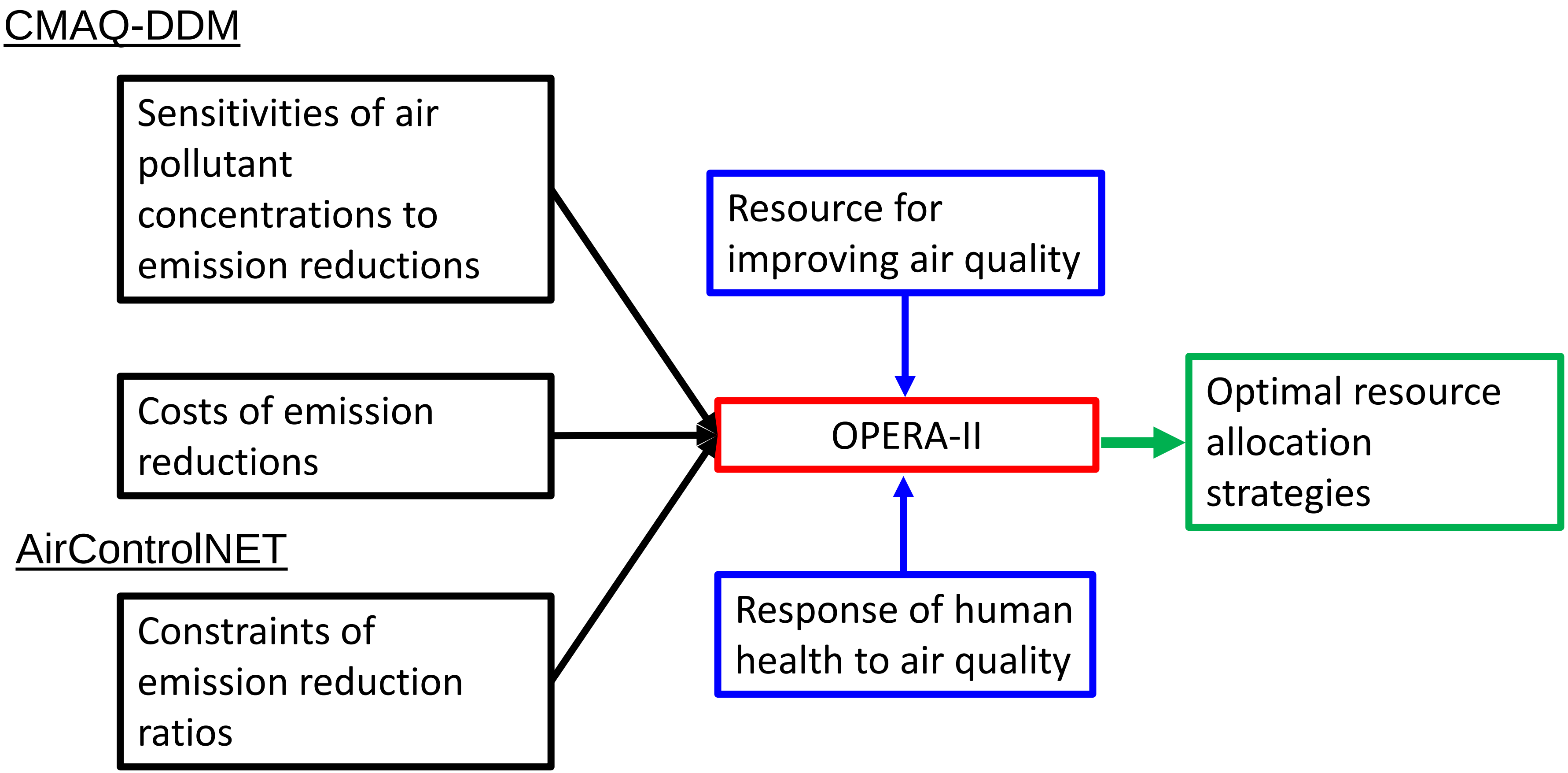
- Reductions in emission reductions from distant regions could be cost-effective for achieving prescribed ozone and $PM_{2.5}$ levels in the cities examined.
- Reducing regional NO*x* and VOC as well as local primary $PM_{2.5}$ emissions was more cost-effective than controlling SO_2 emissions for decreasing ozone and $PM_{2.5}$ concentrations simultaneously.
- A major strength of OPERA-I is its flexibility that allows for changes in regulations, involving agencies, study regions, and etc. to be readily incorporated.

Objective -II

Development of optimal resource allocation strategies (**OPtimal Integrated Emission Reduction Alternatives - II (OPERA-II)**) for:

- achieving largest human health benefits
- at multiple locations simultaneously

Development of OPERA-II



CMAQ-DDM

Sensitivities of air pollutant concentrations to emission reductions

Costs of emission reductions

AirControlNET

Constraints of emission reduction ratios

Resource for improving air quality

OPERA-II

Response of human health to air quality

Optimal resource allocation strategies

OPERA-II Formulation

Decreases in total mortality due to reductions in pollutant concentrations

Maximize $$\sum_{c=1}^{n} \underline{\Delta mortality_{c}}$$

Subject to: $$\sum_{j=1}^{p} Cost_{j,k}\left(\Delta\varepsilon_{j,k}\right) \le R_{k} \qquad k = 1, 2, \ldots, m$$

$$0 \le \Delta\varepsilon_{j,k} \le U_{j,k}$$

$$\Delta mortality_{i} = population \times y_{0} \times \left(e^{\beta \cdot \Delta X} - 1\right)$$

(M Bell et al. 2004; Pope et al. 2002)

where ***c***, ***j*** and ***k*** present the MSAs, precursors and regions, respectively.

n, ***p*** and ***m*** are the number of MSAs, precursors and regions, respectively

Health Effects: Concentration-Response Function

$$\Delta y = y_0\left(1 - e^{-\beta \Delta x}\right) * Population$$

where

- y_0= baseline mortality rate (deaths per 100 people)
- β for PM is 0.014842 per 1 μg/m^3 (Laden et al., 2006)
- β for daily maximum 8-hr average ozone is 0.000795 per 1 ppb (Bell et al., 2005)

RANK	MSA	2010 Population	y_0
1	New York-Newark-Jersey City, NY-NJ-PA	19,567,410	0.01333
2	Los Angeles-Long Beach-Anaheim, CA	12,828,837	0.01146
3	Chicago-Naperville-Elgin, IL-IN-WI	9,461,105	0.01383
4	Dallas-Fort Worth-Arlington, TX	6,426,214	0.01161
5	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	5,965,343	0.01457

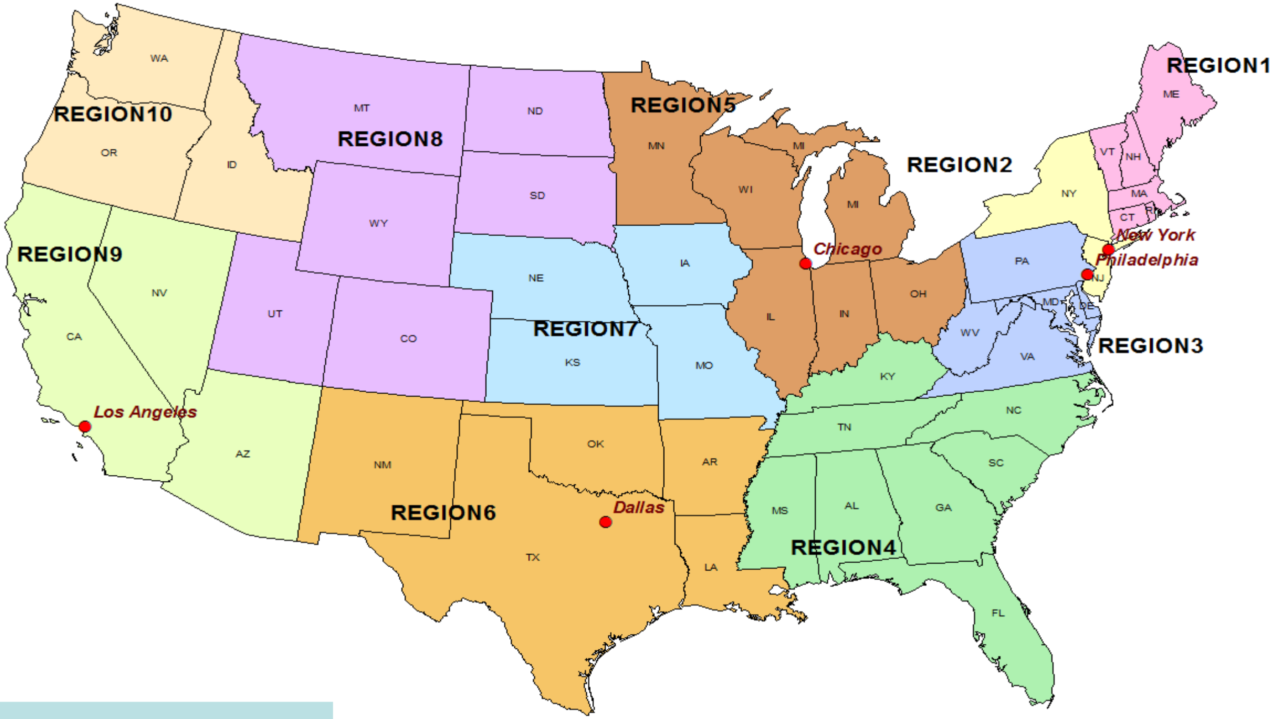
Case Study

-Two pollutants:
ozone and $PM_{2.5}$

-Regional precursors: SO_2, NO_x, VOC and PC

-Ten U.S. EPA Regions

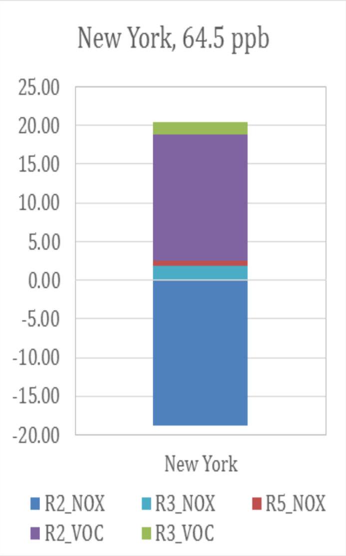
- Five MSAs

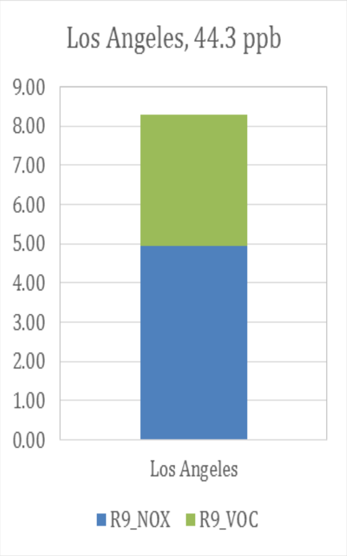


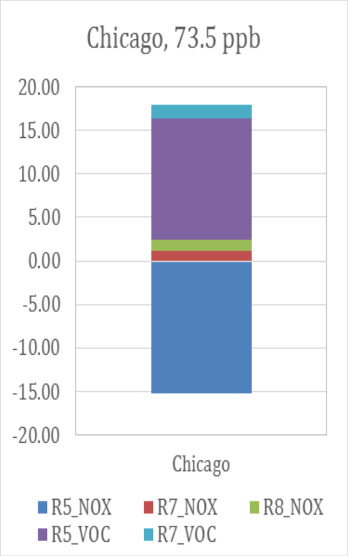
Air Quality Model	U.S. EPA CMAQ-DDM v5.0.1
Meteorological Model	WRF
Horizontal Resolution	12*12 km
Vertical Layer	22 Layers
Simulation Period	August 8 - August 21, 2010

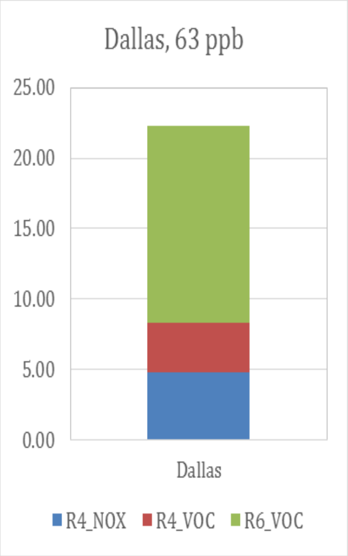
Sensitivity of Ambient Ozone and $PM_{2.5}$

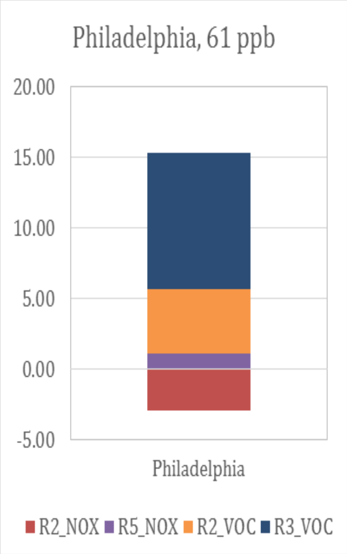
O_3


New York, 64.5 ppb

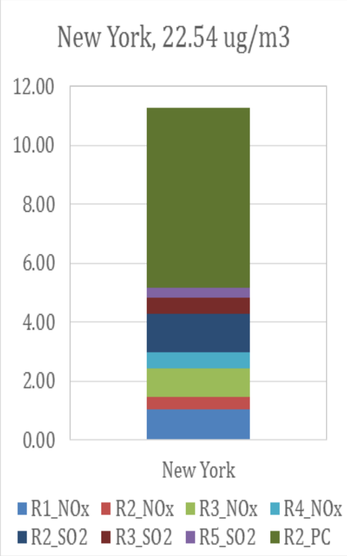

Los Angeles, 44.3 ppb

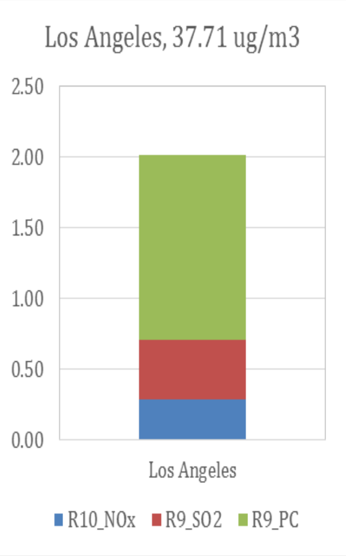

Chicago, 73.5 ppb

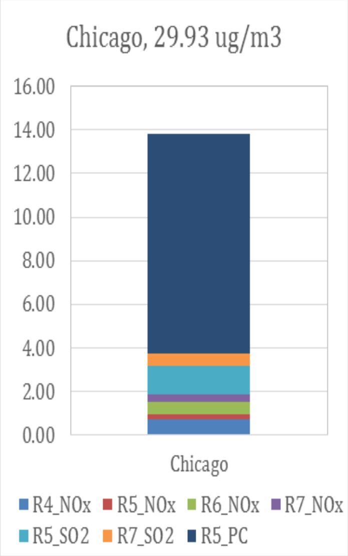

Dallas, 63 ppb

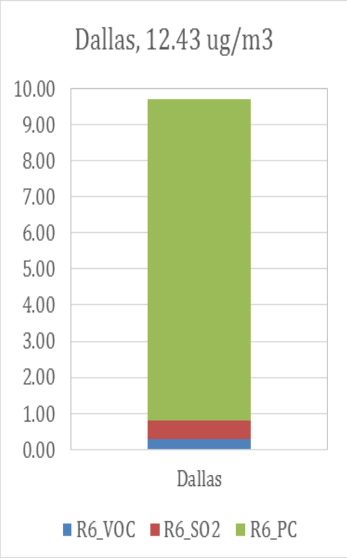

Philadelphia, 61 ppb

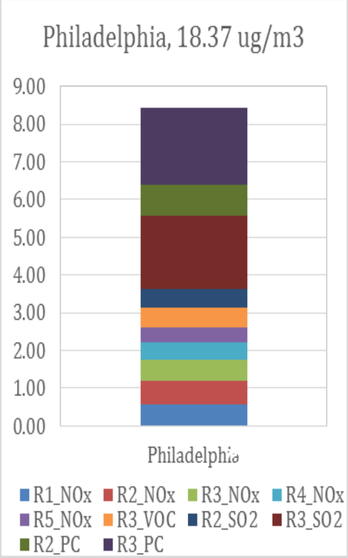
$PM_{2.5}$


New York, 22.54 ug/m3

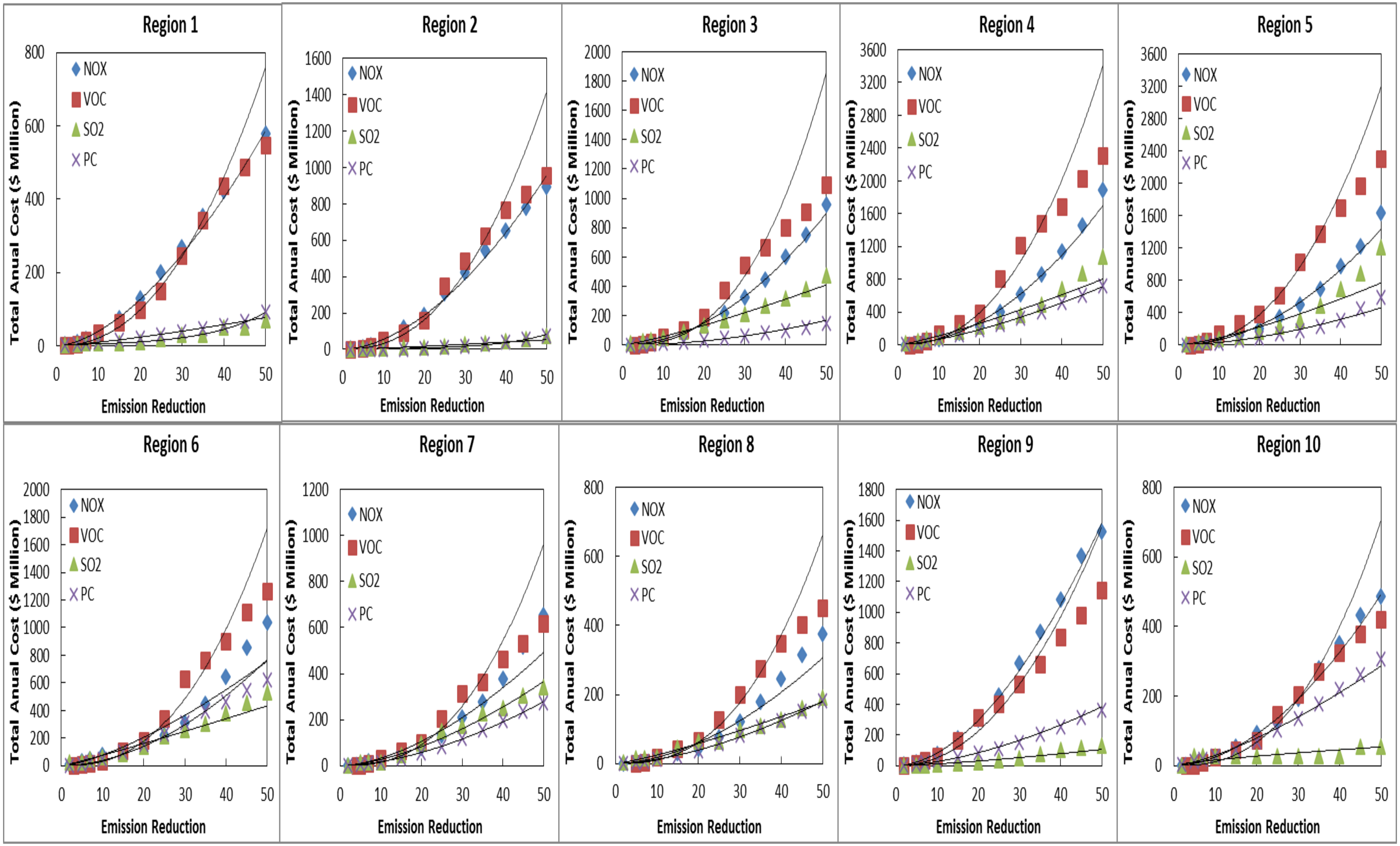

Los Angeles, 37.71 ug/m3


Chicago, 29.93 ug/m3


Dallas, 12.43 ug/m3


Philadelphia, 18.37 ug/m3

Costs of Air Pollutant Emission Controls



Air Quality Control Resources

- Office of Air and Radiation of U.S. EPA (2010) estimates that annual cost values of complying with the Clean Air Act for 2010 were **$43,900** (million 2006$), which included costs of reductions in six major criteria pollutants (VOCs, NOx, SO_2, CO, PM_{10} and $PM_{2.5}$), ammonia (NH_3) and hazardous air pollutants (HAPs) attributed to regional and local controls over the U.S.
- We assume 70% of the total cost could be used to reduce emissions of the four pollutants from regional sources.
- Furthermore, the total of population of the top five U.S. cities accounted for about ~17.5% of the total U.S. pollution in 2010, and the total budget used in our case study is **~$5,400** (=$43,900*0.7*0.175) (millions 2006$).

Results – Emission Reduction

	NOx	VOC	SO_2	PC
Region 1	18.0	8.7	96.0	54.8
Region 2	22.9	18.0	74.0	61.7
Region 3	11.6	~0	50.4	50.9
Region 4	5.8	8.2	16.0	1.2
Region 5	15.1	8.9	37.2	42.4
Region 6	19.3	11.0	8.8	48.7
Region 7	20.4	5.8	29.7	7.5
Region 8	17.2	3.7	17.8	2.4
Region 9	8.5	12.0	89.3	51.9
Region 10	6.5	4.2	~0	~0

- Controls of SO_2 and PC emissions would be the most effective approach to reduce air pollution-related mortality for the five MSAs collectively.
- $PM_{2.5}$ has more significant health effects than ambient ozone does.
- Controls of NOx and VOC emissions are expensive, and ozone-related mortalities are less significant than $PM_{2.5}$-related mortalities

Mortality Avoidance (August 8th ~ August 21st, 2010)

	New York	Los Angeles	Chicago	Dallas- Fort Worth	Philadelphia	All Cities
Ozone-related mortality	700	100	200	200	100	1,300
$PM_{2.5}$-related mortality	11,100	6,700	6,200	2,300	3,200	29,500
Total	11,800	6,800	6,400	2,500	3,300	**~30,800**

- The results show that reductions in $PM_{2.5}$-related mortalities (~29,500) would be much higher than ozone-related mortalities (~1,300) if the funds could be allocated in a way suggested by the results of the resource allocation model.

Responses of Mortality Avoidance to Budget Perturbation

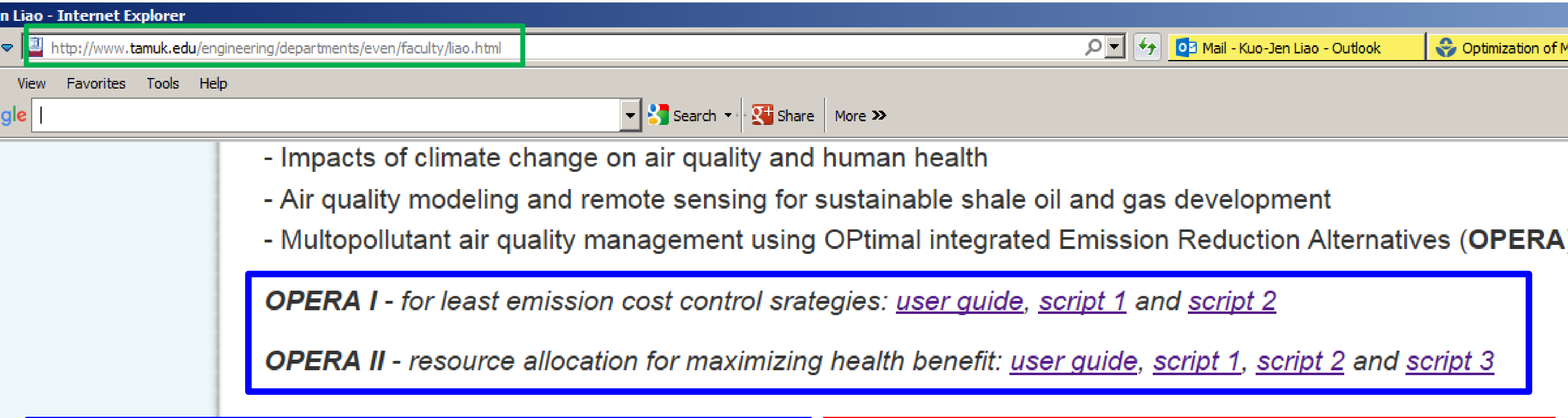
	Budgets (in millions)	Mortality Avoidance	Difference (in percentage)
budgets in 2010	5,400	30,796	-
+20%	6,480	31,727	+2.92
+15%	6,210	31,507	+2.27
+10%	5,940	31,280	+1.62
+5%	5,760	31,123	+0.97
-5%	5,130	30,536	-0.97
-10%	4,860	30,261	-1.62
-15%	4,590	29,968	-2.60
-20%	4,320	29,652	-3.57

Limitations and Uncertainties

- The EPA 1999 emission inventory, used by AirControlNET, may not fully represent current air pollutant emissions and their control costs. More recent emissions and their control costs should be considered in developing resource allocation strategies in the future.
- CMAQ-DDM only simulates first-order sensitivities of air pollutants to emission reductions. It could induce uncertainties in the results of resource allocation modeling.
- The coefficients in the C-R function obtained from previous epidemiologic studies may not apply equally well to all the five MSAs. More detailed analysis of responses of mortalities to changes in air pollutant emissions for different cities will be needed to reduce uncertainties.

Conclusions

- Given the cost values in EPA's CAA assessment, the results of the case study suggest that controls of SO_2 and PC emissions would achieve the most significant health benefits for the five selected MSAs collectively.
- The results also show that the majority of the resource would be used controls of SO_2 and PC emissions from Regions 2, 3, 5, 6 and 9.
- Around 30,800 air pollution-related mortalities could be avoided during the selected period for the five selected MSAs.
- OPERA-II can be used to develop air quality management strategies for differnt seasons and more cities if health responses and air quality sensitivities for different seasons and areas can be determined.



- Impacts of climate change on air quality and human health
- Air quality modeling and remote sensing for sustainable shale oil and gas development
- Multopollutant air quality management using OPtimal integrated Emission Reduction Alternatives (**OPERA**

OPERA I *- for least emission cost control srategies: user guide, script 1 and script 2*

OPERA II *- resource allocation for maximizing health benefit: user guide, script 1, script 2 and script 3*

Script 1
Emission reduction constraints

```
x0 = [0.0;0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0];
lb = [0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0;...
   0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0; 0.0];
ub = [77.5; 96.0; 75.0; 54.8; 75.5; 90.4; 75.7; 61.7;...
   82.4; 96.6; 74.8; 50.9; 79.5; 96.0; 76.0; 51.3;...
   74.7; 93.7; 75.4; 42.4; 73.9; 83.3; 71.4; 48.7;...
   69.0; 82.5; 68.9; 40.4; 66.6; 80.0; 68.2; 40.1;...
   77.7; 89.3; 74.6; 51.9; 76.0; 86.6; 76.0; 49.5];
A = [];
b = [];
Aeq = [];
beq = [];
nonlcon = @costfun_II;
options = optimoptions('fmincon','Display','iter','Algorithm','sqp');
[x,fval] = fmincon(@objectfun_II,x0,A,b,Aeq,beq,lb,ub,nonlcon,options);
```

Script 2
Cost constraints

```
COST_NOX9=93.159*exp(5.4063*x(33));
COST_SO9=5.7752*exp(6.647*x(34));
COST_VOC9=3999.3*x(35)^1.7212;
COST_PM9=32.092*exp(4.5086*x(36));

COST_NOX10=25.889*exp(5.5013*x(37));
COST_SO10=93.624*x(38)^2+6.9851*x(38)+25.057;
COST_VOC10=2136.7*x(39)^1.9832;
COST_PM10=486.13*x(40)^2+333.71*x(40);

c = COST_NOX1 + COST_SO1 + COST_VOC1 + COST_PM1 +...
   COST_NOX2 + COST_SO2 + COST_VOC2 + COST_PM2 +...
   COST_NOX3 + COST_SO3 + COST_VOC3 + COST_PM3 +...
   COST_NOX4 + COST_SO4 + COST_VOC4 + COST_PM4 +...
   COST_NOX5 + COST_SO5 + COST_VOC5 + COST_PM5 +...
   COST_NOX6 + COST_SO6 + COST_VOC6 + COST_PM6 +...
   COST_NOX7 + COST_SO7 + COST_VOC7 + COST_PM7 +...
   COST_NOX8 + COST_SO8 + COST_VOC8 + COST_PM8 +...
   COST_NOX9 + COST_SO9 + COST_VOC9 + COST_PM9 +...
   COST_NOX10+ COST_SO10+ COST_VOC10+ COST_PM10 - 5400;
ceq = [];
```

Summary

- We develop OPERA-I and OPERA-II which can help design multipollutant air quality management strategies.
- OPERA-I allows identification of least-cost control strategies for achieving multipollutant air quality targets at multiple locations simultaneously.
- OPERA-II allows identification of air quality management strategies that maximize human health benefits subject to budget constraints.
- Main pieces of inputs to OPERA-I and II are : (1) sensitivities of air quality to emission changes, (2) cost functions of emission reductions, and (3) concentration-response (CR) functions.
- The case studies show how OPERA-I and OPERA-II can be applied to develop multipollutant air quality management strategies in the U.S.

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