Atmospheric Pollution Research 1 (2010) 296-304

Atmospheric Pollution Research

www.atmospolres.com

A multi–pollutant, risk–based approach to air quality management: Case study for Detroit

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ABSTRACT

In response to the need to further explore and understand the technical needs and challenges presented by implementing a multi–pollutant, risk–based approach to air quality management, a case study was performed for the urban area of Detroit. As part of this case study, two contrasting air quality control strategies were assessed and compared. One strategy mimicked the "status quo", where controls were selected separately to address ozone (O_3) and fine particulate matter ($PM_{2.5}$) nonattainment at monitor locations, while the other strategy reflected a "multi–pollutant, risk–based" approach aimed at further reducing population risk from exposure to ozone, $PM_{2.5}$ and selected air toxics while still addressing ozone and $PM_{2.5}$ nonattainment. This paper describes the technical framework used to apply and evaluate the two contrasting air quality control strategies and describes the relative benefits of each. Based on this case study, we found that the "multi–pollutant, risk–based" approach was able to: (1) achieve the same or greater reductions of $PM_{2.5}$ and O_3 at monitors; (2) improve air quality regionally and across the Detroit urban core for multiple pollutants; (3) produce approximately two times greater monetized benefits for $PM_{2.5}$ and O_3; (4) reduce non–cancer risk; and (5) result in greater net benefits and be more cost effective.

Keywords:
Multi–pollutant
Control strategy
Risk
Benefits
Air quality management

Article History:
Received: 22 April 2010
Revised: 01 July 2010
Accepted: 06 July 2010

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doi: 10.5094/APR.2010.037

1. Introduction

In 2004, the National Research Council (NRC) report *Air Quality Management in the United States* recommended that the U.S. Environmental Protection Agency (EPA) transition from a "pollutant–by–pollutant approach to air quality management to a multi–pollutant, risk–based approach". Since there had not been a complete technical demonstration of the application and evaluation of a multi–pollutant, risk based approach, we decided to undertake a case study focused in one urban area. For this case study, the area of Detroit was chosen due to the multi–pollutant nature of the air quality problems there and the wealth of data available (U.S. EPA, 2008a). The overall goal was to: (1) demonstrate a framework with the available technical tools, methods and data that can be used to apply and evaluate multi–pollutant, risk–based control strategies; and (2) determine the relative benefits of implementing such a framework as compared to a single–pollutant, State Implementation Program (SIP)–based approach to air quality management. To do this, we worked through a process to use our technical tools, methods and data to evaluate the local and regional impacts of changes in criteria and toxic pollutant emissions on air quality from two contrasting air quality management strategies. One strategy reflected a single–pollutant approach, where controls are selected separately to address ozone (O_3) and fine particulate matter ($PM_{2.5}$) nonattainment at monitor locations. We refer to this strategy as the "Status Quo" control strategy. The second strategy, a "Multi–pollutant, Risk–based" control strategy, is aimed at further reducing population risk from exposure to O_3, $PM_{2.5}$ and selected air toxics while still addressing O_3 and $PM_{2.5}$ nonattainment. The results of this assessment are discussed below.

2. Study Design: Technical Framework

As part of this case study, we established a technical framework, as shown in Figure 1, in which our two contrasting strategies could be formulated, modelled and evaluated. In this framework, a control strategy is developed and then modelled using a multi–pollutant emissions inventory, control measures database, and air quality modelling system. Data output from the modelling platform is then used to calculate the resultant change in air quality, for both criteria (O_3 and $PM_{2.5}$) and hazardous air pollutants (CAPs and HAPs), and to inform tools that assess the impact of the control strategy on changes in human health risk and exposure. The results of this assessment could then be used to make changes to the control strategy, if needed. The details on the components of this framework as used for this study are discussed in the following sections.

2.1. Emissions inventory and emissions modeling

To allow for analysis of the air quality impacts of both CAPS and HAPS in this project, we used the 2002 NEI v3.0, with integrated data (U.S. EPA, 2008b). This base year inventory was then projected to create a 2020 future year emissions inventory, taking into account any national rules or "on the books" controls and any growth or decline of an emissions source group. The resulting emissions inventory was then processed with SMOKE (Sparse Matrix Operator Kernel Emissions) for input into the Community Multiscale Air Quality Modeling System (CMAQ) and American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD).

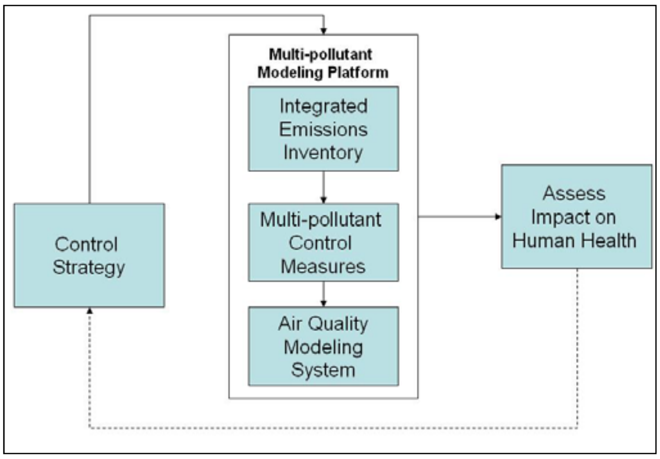

Figure 1. *Multi–pollutant Framework for Technical Assessment.*

Because we modeled local air quality impacts for $PM_{2.5}$ and air toxics using AERMOD, we utilized an emissions inventory that had been updated to be more reflective of the Detroit urban area (Tooly and Wesson, 2009). These updates included: incorporation of the EPA solvent study for eleven solvent utilization categories; activity updates for construction and agriculture equipment and recreational marine vessels; better spatial allocation of county–level recreational marine vessel emissions; and updates to the commercial marine vessel and railroad emissions data. In addition, the Surrogate Tool v3.6 (U.S. EPA, 2009) was used to provide spatial surrogate ratio files that were input to SMOKE for a 1 km x 1 km grid–based allocation of the non–point and non–road emissions for AERMOD modeling of the Detroit urban area.

For the mobile emissions, the most recent version of the Consolidated Community Emissions Processing Tool (CONCEPT) was used to produce link–based mobile emissions for PM and toxics for the seven counties in the Detroit area: Livingston, Macomb, Monroe, Oakland, St. Clair, Washtenaw, and Wayne counties. These counties are part of the Southeast Michigan Council of Governments (SEMCOG), which provides predicted diurnal variability in vehicle miles traveled from the SEMCOG Travel Demand Model (TDM) to CONCEPT. These link–based mobile emissions provide a more refined allocation of mobile emissions for this project and improve the ability to analyze the local–scale impact of mobile emissions on the urban air quality (Strum et al., 2008).

2.2. Multi–pollutant control measures

For this project, we implemented and modeled multi–pollutant control information for control measures in both of our control strategies. We did this so we could represent the true multi–pollutant nature of the selected control measures in both strategies and enable comparison across relevant population exposures to CAPs and HAPs. While there are databases, such as AirControlNet[1)], that can supply control efficiency information for the primarily reduced pollutant(s), it can be difficult to find this same information for other pollutants affected. However, to do true multi–pollutant assessments, this information is critical and so we sought to complete this information for all the control measures in the two strategies. We accomplished this through literature searches, in discussions with EPA source–specific engineers, and by sometimes making simple assumptions about the relationships between directly emitted particles or gaseous species reduced. Table 1 lists the control measures in each of the two strategies and the multi–pollutant control measure efficiencies modeled for each.

[1)] *Available at: http://www.epa.gov/ttnecas1/AirControlNET.htm.*

2.3. Air quality modeling analyses

The air quality modeling is an integral part of the project. It takes inputs from the multi–pollutant emissions inventory and control measures databases and produces information on the change in air quality for input into tools that analyze exposure, risk, and benefits. For this project, we applied EPA's CMAQ photochemical model and AERMOD dispersion model, and combined the concentrations within a grid cell to provide subgrid cell texture via the Multiplicative Hybrid Approach (MHA), as described below. The models were run for the months of January, April, July and October, 2002. More information on the modeling and a model performance evaluation can be found at Wesson et al. (2009).

CMAQ modeling. CMAQ v4.6.1i (Byun and Schere, 2006) offers a multi–pollutant (i.e., ozone, particulates, toxics, acid deposition, and nitrogen loading) capability via a generalized chemistry mechanism, general numerical solver, and comprehensive description of gaseous and aqueous chemistry and modal aerosol dynamics. CMAQ was run as part of the 2002 Modeling Platform (US EPA, 2008c) with a 12 km x 12 km horizontal grid resolution for the "Midwest Domain" centered on Detroit, Michigan, as shown in Figure 2. The meteorological inputs for CMAQ were derived from MM5 data that were processed to create model–ready inputs using the Meteorology–Chemistry Interface Processor (MCIP), version 3.4. Initial Condition and Boundary Conditions were supplied for the Midwest Domain from a complementary CMAQ model run, which was run at a 36 km x 36 km horizontal grid resolution.

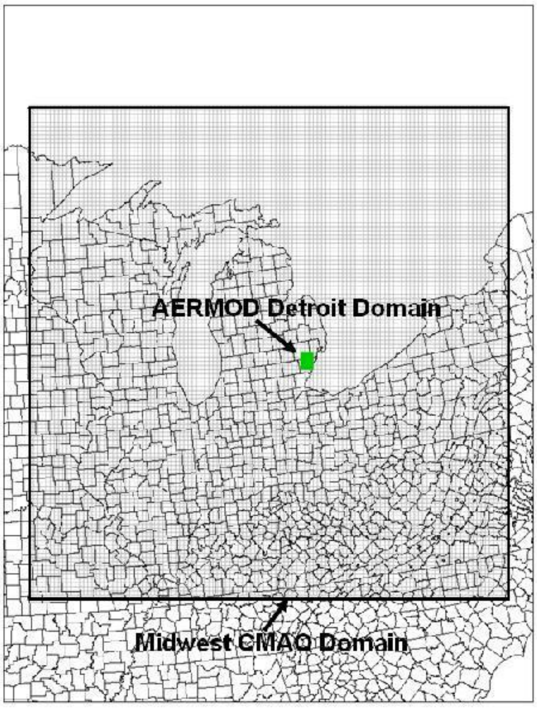

Figure 2. *CMAQ and AERMOD Modeling Domains.*

AERMOD modeling. The AERMOD model (U.S. EPA, 2004a; U.S. EPA, 2004b; U.S. EPA, 2004c) is EPA's preferred air quality dispersion model for regulatory air quality impact assessments of inert pollutants that are directly emitted from a variety of sources for transport distances of up to 50 km. For this study, AERMOD version 0430011 was run for the Detroit urban area. A receptor grid domain was placed at the core of the Detroit urban area, with receptors placed at 1 km spacing across the rectangular grid (e.g., 36 by 48 km) as shown in Figure 2. Since AERMOD predicts concentrations at each of these receptor locations, this dense network of receptors allows for the prediction of the urban gradient for primary pollutants.

A selected number of pollutants were modeled with AERMOD and include: primary organic carbon, elemental carbon, benzene, cadmium, 1,3–butadiene, nickel, naphthalene, manganese, acetaldehyde, diesel particulate matter (DPM), formaldehyde, methylene chloride, and 1,4–dichlorobenzene. The toxics were chosen based on their relative high risk (inhalation; cancer and non–cancer) as measured by the Detroit Air Toxics Initiative (DATI) Study (Simon et al., 2005).

Meteorological data were extracted from the 2002 12 km^2 MM5 data and processed for AERMOD using AERMET. The meteorological data were extracted from the grid cell that included the Detroit Metropolitan Airport (DTW: latitude = 42.22, longitude = –83.35) based on the determination that the meteorology in this grid cell was most representative of the meteorology in the Detroit urban area we are modeling. To account for the dispersive nature of the "convective–like" boundary layer that forms during night-time conditions due to the urban heat island effect, the "urban option" was used.

Multiplicative Hybrid Approach. The Multiplicative Hybrid Approach (MHA) involves combining concentrations from CMAQ and AERMOD within a grid cell to provide subgrid cell texture, as shown in Equation (1).

$$C = CMAQ\_primary * (AERMOD\_rec/AERMOD\_gridavg) + CMAQ\_secondary \quad (1)$$

where *CMAQ_primary* and *CMAQ_secondary* are the primary and secondary CMAQ concentrations of a pollutant within the relevant CMAQ grid cell; *AERMOD_rec* is the concentration of a pollutant at an AERMOD receptor; and *AERMOD_gridavg* is the average concentration of a pollutant for all the AERMOD receptors located within the relevant CMAQ grid cell.

The MHA was applied to $PM_{2.5}$ and all toxic pollutants modeled by AERMOD. For all of the toxic species except for formaldehyde and acetaldehyde, there were no secondarily formed components and Equation (1) was applied with *CMAQ_ secondary* equal to zero. For formaldehyde and acetaldehyde, CMAQ was used to predict the primarily emitted component (*CMAQ_primary*) and secondarily formed component (*CMAQ_ secondary*) and these concentrations were combined with AERMOD predicted values using Equation (1).

To calculate the total $PM_{2.5}$ subgrid concentrations, the use of Equation (1) proved a little more difficult because CMAQ did not split sulfate ($SO_4^{=}$), nitrate (NO_3^{-}), ammonium (NH_4^{+}) into primarily emitted and secondarily formed components, and AERMOD was not used to model all PM species. Therefore, we made the following assumptions: (1) that $SO_4^{=}$, NO_3^{-}, and NH_4^{+} were all or mostly secondarily formed such that they could be represented by CMAQ at the 12 km^2 grid[2)]; (2) that elemental carbon (EC) and primary anthropogenic organic carbon (OC_PA) would not have a secondary formed component such that *CMAQ_secondary* would equal zero; and (3) that sodium particulate matter (ANAJ), chloride particulate matter (ACLJ), and $PM_{2.5}$ accumulation mode unspecified anthropogenic mass (A25J) could be represented at the 12 km^2 grid by CMAQ. Using these assumptions and Equation (1) as appropriate, each of the $PM_{2.5}$ species was calculated and the following equation was used to compute total subgrid $PM_{2.5}$:

$$PM_{2.5} = SO_4+NO_3+NH_4+ORG\_A+1.2*(ORG\_PA)+ORG\_B+EC +A25J+ACLJ+ANAJ \quad (2)$$

where ORG_A and ORG_B are the secondarily formed anthropogenic organic carbon and biogenic organic carbon, respectively, as predicted by CMAQ.

2.4. Control strategy development

This section describes the "Status Quo" control strategy and our approach used to develop the "Multi–pollutant, Risk–based" control strategy. The controls used in the two scenarios are shown in Table 1 and were applied to the 2020 baseline. The costs for these scenarios are shown in Table 1 by emissions sectors. Overall, the cost of the "Status Quo" control strategy was approximately \$56 million while the "Multi–pollutant, Risk–based" control strategy was approximately \$66 million.

"Status Quo" control strategy. The "Status Quo" control strategy was meant to mimic how a state might approach selecting control measures for an O_3 and $PM_{2.5}$ SIP, where controls would be developed separately with a focus on either O_3 or $PM_{2.5}$ attainment, and with a typical least cost approach. To reflect this, we utilized the controls specified for the Detroit area by EPA in its Regulatory Impact Analysis (RIA) of the revised National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ for the annual standard of 15 μg/m^3 and the daily standard of 35 μg/m^3 (U.S. EPA, 2006)[3)]. These control measures were designed to bring the Detroit area into attainment for these standards. For O_3 control measures, we included all of the controls listed as "Selected Control Measures" and "Contingency Measures," as well as some of the "Voluntary Measures" provided in the "Ozone Attainment Strategy for Southeast Michigan" (SEMCOG, 2005) submitted to EPA in June 2005 by Michigan Department of Environmental Quality (MDEQ). As discussed above, though it is not typically part of the SIP process, we included multi–pollutant information for these control measures so that in the air quality assessment the major pollutant(s) as well as any additional criteria or toxic pollutants controlled or created were included.

Multi–pollutant, risk–based control strategy. Before we began to select controls for the "Multi–pollutant, Risk–based" control strategy, we felt that it was important to have a good understanding of the air quality issues in Detroit. To do this, we put together a conceptual model for the Detroit area (U.S. EPA, 2008a). The main points are summarized here.

For $PM_{2.5}$, the Detroit area was classified as nonattainment with the 2001–2003 derived design values being 19.5 μg/m^3 (relative to the 15 μg/m^3 1997 annual standard). Measurements show there are sharp concentration gradients across the area, with some of the highest measured values being at sites close to the city's industrial center. Population data from the 2000 Census shows that there are large numbers of people living near these sites, especially those in and near the city center. Speciation studies at some of these measurement sites (e.g. Dearborn and Allen Park) indicate there is a rather high direct PM component contribution suggesting a benefit of controlling local PM sources. Speciation data and measurement studies suggest that some of this direct PM component is composed of toxic metals such as manganese and nickel, which the DATI report (Simon et al., 2005) indicated as being important pollutants to reduce in concentration in the Detroit area. The emission inventory showed important sources of $PM_{2.5}$ in Detroit to include metal processing, commercial cooking, residential wood burning, and cement manufacturing.

[2)] *In these cases, it was assumed that the concentration of this pollutant would be the same each AERMOD receptor with the corresponding CMAQ grid cell. This allowed the final predicted value of $PM_{2.5}$ to be calculated at a 1 km resolution.*

[3)] *We could not use the controls from the MDEQ SIP for $PM_{2.5}$ when we developed the "Status Quo" control strategy since it had not yet been submitted.*

Table 1. *Control measure information for the "Status Quo" (SQ) and "Multi-pollutant, Risk-based" (MPRB) control strategies* [a]

Control Measure	**Process Type**	**Source Type**	**Control Strategy**	**Approximate Costs (Thousands $)**		**Control Efficiency (%)**						
				SQ	**MPRB**	**PM_{10} and $PM_{2.5}$**	**VOC**	**NO_x**	**SO_2**	**CO**	**Metal HAPs**	**Non-VOC HAPS**
CEM Upgrade and IMF of PM Controls	Mineral Products	Point	SQ			7.7					7.7	
CEM Upgrade and IMF of PM Controls	Metal Processing	Point	SQ			7.7					7.7	
CEM Upgrade and IMF of PM Controls	External Combustion Boilers	Point	SQ			7.7					7.7	
Fabric Filter (Pulse Jet Type)	Mineral Products - Cement	Point	SQ			99					99	
Wet Electrostatic Precipitator (Wire Plate Type)	Chemical Manufacturing	Point	SQ	$21 243		95					95	
Regenerative thermal oxidizer	Industrial Processing	Point	SQ				95					95
Adding Surface Area of Two ESP Fields	External Combustion Boilers	Point	SQ and MPRB [b]			16.75					16.75	
Coal Washing	External Combustion Boilers	Point	SQ and MPRB [b]			45			35		45	
Wet Electrostatic Precipitator (Wire Plate Type)	Metals Processing	Point	MPRB		$31 677	95					95	
Capture Hood Vented to Baghouse	Metals Processing	Point	MPRB			95					95	
Fabric Filter (Pulse Jet Type)	Metals Processing	Point	MPRB			99					99	
Fabric Filter (Mech. Shaker Type)	Metals Processing	Point	MPRB			99					99	
Education and Advisory Program [c]	Residential Wood Combustion	Area	SQ and MPRB			50	50	50	50	50	50	50
NSPS Compliant Wood Stove and Fireplace Inserts [c,d]	Residential Wood Combustion	Area	SQ and MPRB			9.8	8				9.8	8
Conveyorized Charbroilers [c]	ESP for Commercial Cooking	Area	SQ and MPRB			18.5					18.5	
Education and Training Program [c]	Auto Body Refinishing	Area	SQ and MPRB	$3 066		92	18.6				92	18.6
Reformulation for consumer commercial products [c]	Solvent Utilization	Area	SQ and MPRB				8					8
Prohibit use of solvent for cold cleaning with a vapor pressure greater than 1.00 mm Hg at 68 F [b]	Degreasing	Area	SQ and MPRB				6					6
Reduce vapor pressure from 7.8 to 7.0 lbs/in^2 [e]	Fuel Vapor Pressure	Mobile	SQ	$31 385			3.5					
Level 2 Diesel retrofits [e,f]	Heavy duty Diesel Engines	Mobile	MPRB		$31 136	13.7	6.4			17.0	13.7	
On-board Diagnostic (OBD) Inspection and Maintenance [e,g]	Vehicles made in 1996 or later	Mobile	MPRB				9.77	5.31		15.59		

[a] *Control information and costs can be found at: SEMCOG, 2005; U.S. EPA, 2006; U.S. EPA, 2005; Air Improvement Resource, Inc., 2005*
[b] *Units controlled vary per control strategy*
[c] *Applied to the counties of Genesee, Lapeer, Lenawee, Livingston, Macomb, Monroe, Oakland, St Clair, Washtenaw, and Wayne*
[d] *98% control efficiency for $PM_{2.5}$ and PM_{10} and 80% for VOC and non-VOC HAPS with 10% trade-out results in an estimated reduction of 9.8% and 8.0% respectively*
[e] *Applied to the seven SEMCOG counties of Livingston, Macomb, Monroe, Oakland, St Clair, Washtenaw, and Wayne.*
[f] *Assumes 100% implementation for on-road heavy duty diesel engines.*
[g] *Assumes the following to compute the cost and fuel savings: cars tested: 953, 200; test costs: $25, failure rate: 15%, average repair cost: $200; percent fuel savings: 10%; average fuel costs: $3/gallon; average miles travelled: 20 000; average miles per gallon: 24.*

For O_3, the Detroit–Ann Arbor area was classified as a moderate nonattainment area[4)] of the 8–hour ozone standard with the 2001–2003 derived design value being 0.097 ppm (relative to the 0.085 ppm 1997 8–hour standard). Modeling results indicate the area to be "VOC–limited," especially in the urban core, suggesting that reducing volatile organic compound (VOC) emissions, versus nitrogen oxide (NO_X) emissions, would have the greatest impact on reducing O_3 (SEMCOG, 2005). The DATI report (Simon et al., 2005) indicated that there were at least nine VOC species that had significantly high concentrations in the Detroit urban area and that could be identified as contributing the most to the risks. These included 1,4–dichlorobenzene, acrylonitrile, benzene, formaldehyde, methylene chloride, naphthalene, carbon tetrachloride, acetaldehyde, and 1,3–butadiene. Reducing emissions of these pollutants suggests a possible co–benefit of reducing both O_3 and toxic risk, especially if reductions take place in or near the city center where the area is the most "VOC–limited" and the population is high. The emission inventory indicates that important sources of VOCs in the area include on–road and non–road vehicles, solvents, residential wood combustion and some industrial sources.

Using this information, we developed the "Multi–pollutant, Risk–based" control strategy. Our goal was to find control measures that would get at least the same reductions for $PM_{2.5}$ and O_3 at the monitors as the "Status Quo" control strategy achieved, but also to go further in reducing $PM_{2.5}$, O_3 and selected air toxic

[4)] *On September 16, 2004, EPA granted the request made by SEMCOG and MDEQ to reclassify Southeast Michigan from a moderate nonattainment area to a marginal nonattainment area for ozone air pollution.*

concentrations throughout the region, with a particular focus on densely populated areas. To do this we focused on finding population oriented reductions, when possible, and tried to select controls that would offer a co–control opportunity, especially with respect to reducing air toxics. Between the two strategies, we tried to keep similar total reductions for the primary controlled pollutants but make trade–offs among pollutants reduced. We did this to keep the "Multi–pollutant, Risk–based" control strategy from being more successful simply due to larger emission reductions, though we understood that this would not necessarily be the approach a state would take in developing this type of strategy. It should be noted, however, that while the tons reduced were similar between the two strategies, there were differences in the sources controlled or the control measures selected. In many cases, the differences resulted in a greater reduction of pollutants closer to heavily populated areas. Table 2 shows the differences in emissions reductions between the two control strategies. While we did consider control costs by aiming to find cost–effective reductions (i.e. \$ per $\mu g/m^3$ and ppb reduced) amongst our control measure options, we did not use the simple "least cost" methodology of total cost per tons of emissions reduced to decide whether a control measure should be included or not. The controls selected for the "Multi–pollutant, Risk–based" control strategy are listed in Table 1.

2.5. Exposure/risks/benefits analyses

Data from the air quality modeling was used as input into the environmental Benefits Mapping and Analysis Program (BenMAP) and the Human Exposure Model–3 (HEM–3) to assess how the control strategies affect human health. For BenMAP, O_3 and $PM_{2.5}$ concentrations were input from CMAQ for the Midwest domain to capture regional changes, while local effects were captured through the $PM_{2.5}$ concentrations from the MHA. For HEM–3, toxics concentrations were input from the MHA for the Detroit urban area for the AERMOD domain shown in Figure 2.

BenMAP. BenMAP is a desktop PC and geographic information system–based computer program that estimates the health impacts and monetized benefits of population–level changes in air pollution (Abt, 2008). BenMAP applies health–impact functions, which is a well established approach for relating ambient changes in air pollution to changes in the incidence of adverse health impacts (Davidson et al., 2007).

To calculate the economic value of avoided (or incurred) cases of air pollution health impacts, BenMAP multiplies the change in incidence against a per–unit economic value for that endpoint. Using Monte Carlo methods, BenMAP calculates a point estimate for each health impact and monetized benefit estimate as well as a confidence interval around that estimate (Abt, 2008).

In this analysis we employed BenMAP to assess the $PM_{2.5}$ and O_3–related health impacts and monetized benefits of the "Status Quo" and the "Multi–pollutant, Risk–based" control strategies. O_3 and $PM_{2.5}$ concentrations were input from CMAQ for the Midwest domain to capture regional changes, while local effects were captured using the fine–scale $1km^2$ $PM_{2.5}$ concentrations from the MHA.

The use of finely resolved air quality inputs in a health impact assessment requires that special care be taken when specifying the other portions of the analysis, including the population estimates, effect coefficients, and baseline incidence rates. In general, as the spatial scale decreases, national or "generic" data may become less representative (Hubbell et al., 2009). In particular, national or regionalized effect coefficients and baseline incidence rates are less likely to characterize well the risks of air pollution exposure changes or the baseline incidence rate for key health endpoints including mortality, rates of chronic disease such as bronchitis and rates for acute events such as hospital and emergency department admissions. For this analysis we collaborated with the Michigan Department of Environmental Quality to procure ZIP–code level hospitalization rates for key health endpoints including hospital admissions for asthma (ICD–9 493), chronic heart disease (ICD–9 410), chronic bronchitis (ICD–9 491), acute bronchitis and bronchiolitis (ICD–9 466), pneumonia (ICD–9 480–486) and chronic obstructive pulmonary disorder (ICD–9 466, 491, 492, 494, 496).

When estimating health impacts for Detroit, we elected to apply "EPA default" (U.S. EPA, 2010a) $PM_{2.5}$ and O_3 risk estimates because of the relative paucity of Detroit–specific epidemiological studies suitable for health impact analyses. With the exception of the Ito (2003) study, which estimates the change in $PM_{2.5}$–related chronic lung disease hospitalizations in Detroit, we applied effect coefficients drawn from studies that assess air pollution impacts in other portions of the country. We also applied "EPA default" economic valuation functions (U.S. EPA, 2010a).

HEM–3. The Human Exposure Model–3 (HEM–3), Version 1.2.0 (U.S. EPA, 2010b) was used to determine the effect of the two control strategies on human exposures and health risks. Annual average concentrations for the toxic pollutants were calculated using the MHA and input into HEM. Using the Voronoi Neighbor Averaging (VNA) interpolation technique (Abt, 2003), pollutant concentrations were interpolated from the receptor locations to the Census block centroids in the Detroit urban area. Using this data, HEM–3 estimated cancer risks and non–cancer adverse health effects due to inhalation exposure at each block. Cancer risks were computed using EPA's recommended unit risk estimates for toxic air pollutants (U.S. EPA, 2007). The resulting estimates reflect the risk of developing cancer for an individual breathing the ambient air at a given receptor site 24–hours per day over a 70–year lifetime. While this assumption is not quite realistic, it is consistent with EPA's approach to estimating "Maximum Individual Risk," a metric used to inform regulatory decisions.

Non–cancer health effects were quantified using hazard quotients and hazard indices for various target organs. The "hazard quotient" for a given pollutant and receptor site was calculated as the ratio of the ambient concentration of the chemical to the level at which no adverse effects are expected, and the "hazard index" for a given organ was computed as the sum of the hazard quotients for substances that affect that organ. HEM–3 identified receptor locations at which the predicted cancer risk and hazard indices were the highest, and the contributions of the different pollutants to the overall cancer risks and hazard indices. The model also estimated the numbers of people exposed to various cancer risk levels and hazard index levels.

3. Results

Using the currently available tools, methods and data described above, we applied the framework shown in Figure 1 to better understand the impact of the emissions reductions in the two control strategies on air quality and human exposure. To do this, we compared and contrasted the results of the two strategies using a set of five evaluation criteria: (1) What is the air quality at the monitors, especially those exceeding the standard? (2) What is the change in air quality across the urban core and regionally? (3) What are the population weighted and monetized air quality changes for $PM_{2.5}$ and O_3? (4) What is the effect on total cancer and non–cancer risk? (5) How do the net benefits and cost effectiveness for the overall strategy compare? Below we discuss the results of these five criteria.

Table 2. *Comparison of annual emissions reductions between the "Status Quo" and "Multi-pollutant, Risk-based" control strategies*

Pollutant	2020 Base (tons)	"Status Quo"		"Multi-Pollutant, Risk-Based"		Total tons Difference
		Tons Reduced	% Change from Base	Tons Reduced	% Change from Base	
$PM_{2.5}$	31 485	1 747	6%	3 183	10%	+ 1 436
SO_2	187 525	10 297	5%	2 429	1%	- 7 868
VOC	104 872	5 814	6%	8 623	8%	+ 2 808
NO_X	118 432	31	0.03%	2 016	2%	+ 1 985
CO	424 426	1 546	0.4%	64 187	15%	+ 62 641
Acetaldehyde		18.35		38.72		+ 20.38
Benzene		130.25		138.73		+ 8.84
1,3-Butadiene		41.52		13.19		- 28.33
1,4-Dichlorobenzene		15.28		15.28		No Change
Formaldehyde		19.16		44.50		+ 25.34
Methylene Chloride		1.63		0		- 1.63
Naphthalene		16.74		4.24		- 12.50
Manganese		0.86		8.50		+ 7.64
Cadmium		$9x10^{-4}$		$2x10^{-4}$		$- 7x10^{-4}$
Nickel		0.19		0.05		- 0.14
Diesel PM		0		30.70		+ 30.70

3.1. Predicted air quality at the monitors

Using EPA's Model Attainment Test Software (MATS) (Abt, 2009), the modelled data for January, April, July and October, 2002 and each of the future year scenarios (i.e. 2020, 2020 with the "Status Quo" control strategy, and 2020 with the "Multi–pollutant, Risk–based" control strategy) were used to compute O_3 and $PM_{2.5}$ design values (DVs). DV calculation for both O_3 and $PM_{2.5}$ used ambient monitoring data from 2000–2004. For $PM_{2.5}$, an annual average DV[5)] was calculated using the four months of modelled data. For O_3, the July data were used to compute an 8–hour maximum DV from the 4^{th} high monitored 8–hour ozone values and the maximum modelled baseline 8–hour ozone concentrations with a minimum allowable threshold of 60 ppb.

We then compared the DVs from both of the control strategies to understand how the control measures selected in each affected the predicted air quality at the monitors. For $PM_{2.5}$, the "Multi–pollutant, Risk–based" control strategy showed much higher decreases in the $PM_{2.5}$ annual average DVs, especially at the monitors predicted to be above 15 µg/m^3. For example, the Dearborn monitor (ID #261630033) had a predicted annual average DV of 18.6 µg/m^3 for 2020. While the "Status Quo" control strategy brought this value down to 15.6 µg/m^3, the predicted DV with the "Multi–pollutant, Risk–based" control strategy in place was 13.3 µg/m^3. Similar results were shown for the N. Delray (ID #261630015) and Wyandotte (ID #261630036) monitors where the values of 2020 base versus "Status Quo" control strategy versus "multi–pollutant, risk–based" control strategy at the two monitors were 16.4 µg/m^3 vs. 13.6 µg/m^3 vs. 11.8 µg/m^3 and 15.4 µg/m^3 vs. 12.9 µg/m^3 vs. 12.3 µg/m^3, respectively.

For O_3, all monitors within the Detroit area were predicted to have a 2020 O_3 8–hr maximum DV below 80 ppb. With application of the "Multi–pollutant, Risk–based" control strategy, many of these monitor DVs decreased by 1–3 ppb, which was equal to or more than the predicted reductions resulting with the application of the "Status Quo" control strategy. The Macomb monitor (ID #260991003) was one of the most impacted by the control strategies with a predicted ozone 8–hr maximum DV of 78.7 ppb for 2020, 78.6 ppb with the "Status Quo" control strategy, and 78.4 ppb with the "Multi–pollutant, Risk–based" control strategy.

[5)] *Because of the lack of a full year of air quality modeling data for each future year scenario, we do not calculate the daily $PM_{2.5}$ DV for this analysis.*

3.2. Air quality locally and regionally

Analyzing the air quality locally in the Detroit urban area and regionally in the area outside the urban core, we found that the "Multi–pollutant, Risk–based" control strategy almost always produced greater reductions in $PM_{2.5}$ and ozone concentrations. For air toxics, we examined the air quality changes in the urban core of Detroit as defined by the AERMOD domain shown in Figure 2. We found that for most of the air toxics, the control measures in the "Multi–pollutant, Risk–based" control strategy almost always resulted in greater reductions than those from the "Status Quo" control strategy. We further examined the effect of these reductions with respect to population exposure in the following two criteria.

3.3. PM and O_3 benefits

We estimated $PM_{2.5}$ and O_3–related health impacts and monetized benefits with BenMAP using the approach described above, quantifying both a point estimate as well as 95% confidence intervals. Both control strategies yield substantial health benefits in the form of hundreds of avoided premature mortalities, dozens of avoided chronic illnesses including acute myocardial infarctions and chronic bronchitis, and dozens of avoided acute effects including asthma exacerbations, respiratory and cardiovascular hospitalizations and emergency department visits (Table 3). Consistent with previous EPA analyses assessing $PM_{2.5}$ and O_3–related impacts, premature mortality represents the largest single monetized benefits category. This fact is due to the size of the economic valuation estimate used to value this endpoint ($5.5M in 2000$)[6)].

As shown in Table 4, the total monetized benefits were approximately $1.1 B for the "Status Quo" control strategy versus $2.4 B (2006$, 3% discount rate) for the "Multi–pollutant, Risk–based" control strategy, relative to the 2020 baseline. For $PM_{2.5}$, we estimated both the local and regional benefits[7)]. The local

[6)] *Readers interested in additional details regarding the valuation estimates used to monetize each health endpoint may refer to the 2010 Transport Rule RIA (U.S. EPA, 2010a).*

[7)] *We define "local" as the Detroit urban area modelled with MHA and shown in Figure 2, and we define "regional" as the area within the Midwest CMAQ Domain but not included in the "local" area.*

benefits were $610 million and the regional benefits were $520 million for the "Status Quo" control strategy while the local and regional benefits were $1,600 million and $810 million, respectively for the "multi–pollutant, risk–based" control strategy. For O_3, we analyzed the benefits for the entire Midwest CMAQ domain, which were $0.9 million for the "Status Quo" control strategy and $2.1 million for the "Multi–pollutant, Risk–based" control strategy[8)].

Table 3. *$PM_{2.5}$ and Ozone–related health impacts avoided in 2020 (95% confidence intervals)*

Health Effect	Status-quo [a]	Multi-pollutant, risk-based [a]
PM-Related endpoints		
Premature Mortality		
Pope et al. (2002) (age >30)	59 (23-95)	130 (49-200)
Laden et al. (2006) (age >25)	150 (82-220)	320 (180-470)
Infant (< 1 year)	0.2 (-0.2-0.7)	0.6 (-0.5-1.7)
Chronic Bronchitis	39 (7.2-71)	82 (15-150)
Non-fatal heart attacks (age > 18)	91 (34-150)	220 (79-350)
Hospital admissions-respiratory (all ages)	16 (7.7-23)	32 (16-48)
Hospital admissions-cardiovascular (age > 18)	31 (21-36)	65 (46-75)
Emergency room visits for asthma (age < 18)	72 (43-100)	160 (96-230)
Acute bronchitis (age 8-12)	47 (-1.6-95)	210 (-7-420)
Lower respiratory symptoms (age 7-14)	1,100 (530-1 700)	2 500 (1 200-3 700)
Upper respiratory symptoms (asthmatics age 9-18)	830 (260-1 400)	1,900 (590-3 200)
Asthma exacerbation (asthmatics 6-18)	1 000 (110-2 800)	2,300 (250-6 300)
Lost work days (ages 18-65)	7 200 (6 300-8 100)	16 000 (14 000-18 000)
Minor restricted-activity days (ages 18-65)	43 000 (36 000-50 000)	93 000 (79 000-110 000)
Ozone-related endpoints		
Premature mortality		
Bell et al. (2004) (all ages)	0.09 (0.04-0.015)	0.24 (0.11-0.38)
Levy et al. (2005) (all ages)	0.45 (0.33-0.57)	1.1 (0.8-1.4)
Hospital admissions-respiratory causes (ages > 65)	0.55 (0.08-1.1)	0.6 (0.08-1.1)
Hospital admissions-respiratory causes (ages <2)	0.7 (0.36-1)	1.5 (0.8-2.2)
Emergency room visits for asthma (all ages)	0.57 (0-1.6)	1.6 (-0.8-4)
Minor restricted-activity days (ages 18-65)	800 (410-1 200)	1 700 (870-2 600)
School absence days	290 (110-470)	620 (240-1 000)

[a] Estimates rounded to two significant figures; column values will not sum to total value.

3.4. Cancer and non–cancer risk

For the year 2020, cancer risks and non–cancer hazard indices were estimated using HEM–3 for the baseline case and for the two control strategies. Cancer risks and non–cancer hazard indices were estimated for 1,3–butadiene, acetaldehyde, benzene, cadmium compounds, formaldehyde[9)], methylene chloride, naphthalene, nickel compounds, and 1,4–dichlorobenzene. Because EPA has no cancer unit risk estimates for diesel engine emissions and manganese compounds, only non–cancer hazard indices were estimated for these pollutants.

For both control strategies, the largest contributor to maximum individual cancer risk was cadmium compounds, and the largest contributor to cancer incidence was benzene. There were no significant differences in maximum individual cancer risk or cancer incidence between the two control strategies. The highest non–cancer hazard index (neurological) was driven by manganese, and was 3 for the "Status Quo" control strategy and 2 for the "Multi–pollutant, Risk–based" control strategy. Under the "Multi–pollutant, Risk–based" control strategy, there were about 70 percent fewer people above a hazard index of one.

These results suggest that, to have a more significant impact on cancer risk, it would be important to prioritize emissions controls based on HAP risk. For example, in this study we focused mostly on reducing total VOC emissions in order to achieve O_3 concentration reductions. Though we did choose these VOC emissions reductions to be from population–oriented sources, we might have achieved greater cancer risk reductions if we had also considered how to include emissions reductions of the HAPs contributing the most to the risk and incidence, such as cadmium and benzene. Of course, since our goal was also to reduce O_3, we would have needed to consider trade–offs between possible emissions reduction scenarios to achieve both the cancer risk reduction and the ozone reductions. This type of scenario demonstrates well the type of considerations that would be part of a policy–maker's job in implementing a multi–pollutant, risk–based approach to air quality management.

3.5. Net benefits and cost effectiveness

While both strategies produce significant benefits, the "Multi–pollutant, Risk–based" control strategy generated substantially larger per–person reductions in $PM_{2.5}$ and O_3 and monetized health benefits. Table 5 summarizes the total monetized benefits for each strategy. The "Multi–pollutant, Risk–based" control strategy produced over 2x the monetized benefits as the "Status Quo" control strategy–approximately $2.4 B versus $1.1 B (2006$, 3% discount rate), respectively.

The cost of the "Multi–pollutant, Risk–based" control strategy was slightly larger than the "Status Quo" control strategy–about $56 million versus $66 million (2006$), respectively. However, the cost:benefit ratio for the "Multi–pollutant, Risk–based" strategy was significantly more favourable: 36:1 versus 20:1. Moreover, the cost efficiency, in $ per $\mu g/m^3$ and ppb reduced, was substantially lower for the "Multi–pollutant, Risk–based" control strategy.

3.6. Limitations and uncertainties

As with any complex analysis, the estimates presented here are subject to a number of important limitations and uncertainties. For example, this analysis is based on air quality modelling which relies on inputs of meteorological data, spatial and temporal allocations of total emissions, and speciated control efficiencies for each control measure. There are uncertainties inherent in the formulation of the air quality models, as well as the data input to the models. The predicted air quality concentrations are also used in this study to estimate population exposure, relying on health impact assessments and estimates of incidence rates, both of which hold their own uncertainty, as discussed in previous sections.

8) This analysis omits other important health, welfare and ecological categories including SO_2 and NO_2-related health impacts, recreational visibility and changes in terrestrial and aquatic acidification among others. We exclude other categories due to our inability to quantify impacts and monetize benefits. Were they included, these categories might affect the distribution of benefits among the two strategies.

9) The formaldehyde cancer unit estimate of $5.5x10^{-9}$ per $\mu g/m^3$ was used, which was based on a Chemical Industry Institute of Toxicology analysis. This value is substantially lower than the current IRIS value of $1.3x10^{-5}$ per $\mu g/m^3$. A new EPA IRIS assessment is underway.

Table 4. *Monetary value of avoided $PM_{2.5}$ and ozone–related health impacts in 2020 (2006$, 3% discount rate)*[a]

Health Effect	Pollutant	Status quo	Multi-pollutant, risk-based
Premature Mortality (Pope et al. 2002 PM mortality and Bell et al. 2004 ozone mortality estimates)	$PM_{2.5}$ and O_3	$420 ($58-$950)	$880 ($120-$2,000)
Premature Mortality (Laden et al. 2006 PM mortality and Levy et al. 2005 ozone mortality estimates)	$PM_{2.5}$ and O_3	$1 100 ($170-$2 300)	$2,300 ($360-$4 800)
Chronic Bronchitis	$PM_{2.5}$	$19 ($1-$88)	$40 ($2-$190)
Non-fatal heart attacks	$PM_{2.5}$	$11 ($2-$28)	$23 ($4-$58)
Hospital admissions-respiratory	$PM_{2.5}$ and O_3	$0.2 ($0.1-$0.3)	$0.45 ($0.22-$0.67)
Hospital admissions-cardiovascular	$PM_{2.5}$	$1 ($0.5-$1.2)	$2 ($1-$2.5)
Emergency room visits for asthma	$PM_{2.5}$ and O_3	$0.03 ($0.01-$0.04)	$0.06 ($0.03-$0.1)
Acute bronchitis	$PM_{2.5}$	$0.01 ($-0.001-$0.02)	$0.00 ($-0.001-$0.05)
Lower respiratory symptoms	$PM_{2.5}$	$0.02 ($0.01-$0.04)	$0.05 ($0.02-$0.1)
Upper respiratory symptoms	$PM_{2.5}$	$0.02 ($0.01-$0.06)	$0.05 ($0.01-$0.13)
Asthma exacerbation	$PM_{2.5}$	$0.05 ($0.004-$0.2)	$0.12 ($0.009-$0.5)
Lost work days	$PM_{2.5}$	$1.1 ($0.98-$1.3)	$1.1 ($0.98-$1.3)
Minor restricted-activity days	$PM_{2.5}$ and O_3	$2.5 ($1.3-$3.8)	$5.5 ($2.2-$2.9)

[a] *Estimates rounded to two significant figures.*

While the uncertainties above are important, they do not diminish our confidence in our principal finding: that a multi–pollutant, risk–based approach to air quality management is superior to the "status quo" approach. This study illuminates the importance of linking together air quality information and its estimated impact on health, as shown in Figure 1, to allow for better informed control strategy development and to encourage increased emphasis on multi–pollutant, risk–based emissions reductions.

Table 5. *Comparison of annual costs and benefits for the "Status Quo" and "Multi–pollutant, Risk-based" control strategies*

		"Status Quo"	"Multi-pollutant, Risk-Based"
Total Benefits (M 2006$)		$1 127	$2 385
Change in population-weighted $PM_{2.5}$ Exposure ($\mu g/m^3$)	Regional	0.16	0.1666
	Local	0.2703	0.7211
Change in population-weighted O_3 Exposure (ppb)	Regional	0.0005	0.0006
	Local	0.0318	0.0583
Total Costs (M 2006$)		$56	$66
Cost per $\mu g/m^3$ $PM_{2.5}$ reduced		$0.50	$0.32
Cost per ppb O_3 reduced		$2.6	$0.58
Net Benefits (M 2006$)		$1 071	$2 319
Benefit-Cost Ratio		20.1	36.1

4. Summary

Based on our evaluation, we were able to achieve our stated goals: (1) to define and demonstrate the use of a technical framework in which to implement and evaluate a multi–pollutant, risk–based approach to air quality management; and (2) to compare and contrast the results of applying a SIP–based, "status quo" approach to emissions reductions to a "multi–pollutant, risk–based" approach. Compared to the "Status Quo" control strategy, we found that the "Multi–pollutant, Risk–based" control strategy: (1) achieved the same or greater reductions of $PM_{2.5}$ and O_3 at monitors; (2) showed improved air quality regionally and across the Detroit urban core for multiple pollutants; (3) produced approximately two times greater monetized benefits for $PM_{2.5}$ and O_3; (4) reduced non–cancer risk; and (5) resulted in greater net benefits and was more cost effective. While this case study is only one example of such an approach and issues may vary from area–to–area, we believe that this study allowed a better understanding of the technical tool, methods and data that could be used and the iterative process that will be needed between the policy considerations and the technical analysis for implementing a multi–pollutant, risk–based approach to air quality management.

Acknowledgements

We would like to acknowledge Mary Lee Hultin and Catherine Simon of MDEQ and Sarah Lyon Callo of the Michigan Department of Community Health for their assistance with this project. At US EPA, we would also like to acknowledge Venkatesh Rao for assistance with the conceptual model for Detroit; Madeleine Strum, Lee Tooly, Marc Houyoux, and Rich Mason for their assistance with the emissions inventory data; Elineth Torres and Robin Langdon for assistance with collecting multi–pollutant control measure information; Roger Brode and Sharon Phillips with their assistance with the air quality modeling; Louise Camalier and James Thurman for assistance with post–processing the air quality modeling data; and Darryl Weatherhead and Larry Sorrels for their assistance with the control measure and cost data. We would also like to acknowledge Chris Allen, Allan Beidler, Darrell Ensley, and Nancy Hwang of Computer Science Corporation for their assistance with processing the emissions data and running the air quality models. Lastly, we'd like to acknowledge Joan Weidner of SEMCOG for her assistance with the southeast Michigan transportation data and Alison Pollack and Michele Jimenez of Environ for their assistance in running CONCEPT for southeast Michigan.

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