TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **49**: PM-192-198

Designing Optimal Strategies to Attain the New U.S. Particulate Matter Standards: Some Initial Concepts

Stanley R. Hayes and Julian R. Marshall
ENVIRON International Corporation, Emeryville, California

ABSTRACT

This paper proposes that a fundamental principle for designing optimal strategies to attain new U.S. particulate matter (PM) standards be minimization of community and susceptible group exposure to, and inhaled dosage of, ambient PM. Properly done, such minimization maximizes human health risk reduction. To illustrate implementation of such a principle, an initial prototype model, PM Exposure (PMEX), is described that calculates PM exposure and inhaled dosage as figures-of-merit for control strategy optimization. The model accounts for age-occupation and susceptible group activity patterns, indoor-outdoor concentration differences, and geographical location. Modeling results are presented for a hypothetical example, apportioning inhaled dosage among different classes of sources, under alternative assumptions about the relative potency of different PM species categories. The results, while preliminary, demonstrate that conclusions about source class contribution based on inhaled dosage can be appreciably different than those based on ambient air measurements or emission inventories.

INTRODUCTION

In July 1997, the U.S. Environmental Protection Agency (EPA) promulgated new national ambient air quality standards for particulate matter (PM).[1] EPA based its action[2] in large part on community studies reporting statistical associations between ambient PM and a range of adverse public health effects, including premature death, increased hospital admissions, and emergency room visits (primarily among the elderly and individuals with cardiopulmonary disease); increased respiratory symptoms and disease (among children and individuals with cardiopulmonary disease such as asthma); and decreased lung function (particularly in children and individuals with asthma).

IMPLICATIONS

In July 1997, the U.S. Environmental Protection Agency promulgated new national ambient air quality standards for particulate matter. Nonattainment areas will be required to develop control strategies providing for sufficient emission reductions to attain these standards. In view of the potential health significance and substantial cost of those strategies, it is an important matter of public policy that they be designed to achieve the greatest health risk reduction feasible, in the most cost-effective manner. This paper proposes a methodology that, along with other traditional means, will provide policy-makers with tools for designing optimal strategies to attain the new standards.

Following promulgation of these standards, attention is now turning to their implementation. Nonattainment areas will be required to develop control strategies providing for sufficient emission reductions to attain the standards. In view of the potential public health significance and substantial cost of those strategies, it is important that they be designed optimally, to achieve the greatest health risk reduction feasible, in the most cost-effective manner.

Typically, control strategies are evaluated by their effect on ambient air quality, rather than on health risk per se. Attainment is determined on an air quality basis and is judged to have occurred when the design value, a measure of current ambient air quality defined in the standard (e.g., the highest three-year average of the 98th-percentile concentration at any monitor), is reduced to the concentration level specified by the standard. Control measures constituting a strategy are usually chosen based on such traditional criteria as emission tonnage reduction, cost per ton of reduction, engineering feasibility, and regulatory acceptability rather than directly by their risk reduction potential.

Suppose, however, that more than one combination of control measures leads to attainment. Even if alternative combinations all affect the area-wide design value similarly, it could be that each affects the spatial and temporal patterns of ambient concentrations differently. If so, aggregate community exposure (and resulting health risk) could vary among alternatives, particularly if people (especially those in susceptible groups) are non-uniformly distributed geographically.

Moreover, the species categories composing PM (e.g., sulfates, nitrates, organics, metals, and crustal material) are widely diverse chemically and physically. Different control measure combinations could well differ in the mix of PM species categories whose emissions they reduce. Although new research is under way, uncertainty exists about the identity (-ies) of the PM species that are most closely associated with the health effects of concern. If indeed all PM species are equally associated with those effects, no distinction among control measures on the basis of PM species categories controlled need be made. If not, however, measures directed at PM species not associated with the health effects under concern would be ineffective in reducing their incidence. Either more money than necessary would be spent on controls because of the inclusion of ineffective measures, or worse, little or no health risk reduction would be achieved.

GUIDING PRINCIPLE FOR OPTIMAL PM ATTAINMENT STRATEGIES: MINIMIZATION OF EXPOSURE AND INHALED DOSAGE

How should the control strategy designer select from among the alternative combinations of control measures available? Absent risk-based criteria to guide control program design, the relative importance of controls on different source classes (e.g., motor vehicles, power plants, other industrial facilities, and blowing dust) may well be judged by the size of their contribution to ambient PM concentrations at the design value monitor(s), or by their fractional contribution to area-wide emissions of primary PM (directly emitted) and precursors of secondary PM (formed in the atmosphere).

However, risk-based criteria can also be useful in distinguishing among different control measure combinations. It follows logically that health risk across a community is fundamentally related to aggregate exposure, particularly of susceptible groups. The higher the PM concentrations, the more people exposed in those groups; and the greater their exposure and inhaled dosage, the higher the risk. One would expect health risk, therefore, to be related not just to the design value but also to the community-wide, spatially, and temporally varying pattern of PM concentrations, for which the design value may be an imperfect surrogate.

The design values for the PM_{10} standards and the 24-hr $PM_{2.5}$ standard are determined based on the highest concentrations occurring at a single monitor. However, it seems possible, if not likely, that different control measure combinations could affect PM spatial and temporal patterns in different ways, even if all reduce ambient concentrations at the design value monitor by the same or a similar amount. This could also be the case for the $PM_{2.5}$ annual standard, whose design value is determined from the highest concentrations occurring at either a single monitor or averaged across multiple monitors. A multiple-monitor average is thought to better match the air quality indicator used by the community studies forming the basis of the standard. Depending on the design of the monitoring network, one would expect a multiple-monitor design value to be a better indicator of PM spatial and temporal patterns, and thus health risk, than one based on a single monitor. However, given the complexity of those patterns, it would still not be surprising if different combinations of control measures could result in different PM spatial and temporal patterns, even if all reduce the multiple-monitor design value similarly.

In designing a control strategy, the standard criteria for evaluating control measures (e.g., reduction tonnage, cost per ton, engineering feasibility, and regulatory acceptability) are important and should be considered. This paper proposes that, in addition to these more traditional criteria, the following exposure-based criterion be included as a fundamental principle to guide control strategy design: to the extent feasible, PM control strategies should be designed to minimize community and susceptible group exposure to, and the inhaled dosage of, that portion of ambient PM believed to contain the species of health concern.

Minimization of PM exposure and inhaled dosage is equivalent to maximization of PM health risk reduction. Such equivalence is important, because it means that it is not necessary to be certain of the actual magnitude of PM-induced risk to recognize that reducing exposure to, and the inhaled dosage of, those PM species posing the risk will, in turn, reduce risk. Use of exposure and inhaled dosage as surrogates for health risk helps to simplify incorporation of risk minimization into PM control strategy design. Moreover, the use of integrative measures such as exposure and inhaled dosage as figures-of-merit will help control strategy designers account for the possibilities (if not likelihood) that (1) different control measures would affect subregions within an area differently; (2) people (particularly susceptible groups) are non-uniformly distributed geographically across those areas; and (3) control measures that do not significantly affect the design value might still reduce exposure substantially in some subregions.

DESCRIPTION OF INITIAL PROTOTYPE OF PM EXPOSURE (PMEX) MODEL

Practical application of the guiding principle above can be accomplished using currently available exposure modeling techniques. Although development of such PM exposure models is in its early stages, this paper describes an initial prototype version of the PM Exposure (PMEX) model. PMEX calculates PM personal exposure and inhaled dosage, allowing for different assumptions about the relative potencies of different PM species categories and accounting for (1) age-occupation or susceptible group activity pattern, including physical exercise level; (2) indoor-outdoor differences; and (3) geographical location.

Basic Equations

The PMEX model calculates exposure and inhaled dosage for different age-occupation or susceptible groups, each group characterized by a user-specified activity pattern. An activity pattern is a sequence of hourly assignments to a microenvironment (home, work, vehicle, near roadway, or outdoors), physical exercise level (resting, light, moderate, or heavy), and geographic location. To allow for the possibility that future research might determine that various PM categories differ in their relative potency, a relative potency-weighted version of inhaled dosage is calculated. The basic exposure and relative potency-weighted inhaled dosage equations solved by PMEX are

$$E_j = \sum_{i=1}^{N} I/O_i \; \phi_{ij} \; C_{N\text{-}hr\,ij} \qquad (1)$$

$$D_j = \beta_j \sum_{i=1}^{N} V_i \; I/O_i \; \phi_{ij} \; C_{N\text{-}hr\,ij} \qquad (2)$$

where E_j is exposure (in μg/m^3 - hours) for PM category$_j$, D_j is inhaled dosage (in μg) for PM category$_j$, N is the number of hours in the period of interest (24 hr for a single day or 8760 hours for a year), V_i is the pulmonary ventilation rate (in m^3/hour) during hour$_i$, I/O_i is the indoor-outdoor ratio for the microenvironment in which exposure occurs during hour$_i$, $C_{N\text{-}hr\,ij}$ is the N-hour average concentration for PM category$_j$ at the exposure location during hour$_i$, and ϕ_{ij} is the multiple or fraction of $C_{N\text{-}hr\,ij}$ occurring in hour$_i$.

Adapting the PM classification terminology in previous PM_{10} receptor modeling studies (see the summary in EPA's PM Criteria Document[3]), the PMEX model considers six different PM species categories: primary geological, primary construction, primary motor vehicle exhaust, secondary ammonium sulfate, secondary ammonium nitrate, and other. Category definition may be modified in future work to become more specific to $PM_{2.5}$, as appropriate. Currently, PM standards are mass-based and do not distinguish among PM categories. To allow for the possibility that future research may find differences in potency among categories, eq 2 multiplies dosage by β_j, a relative potency weight for PM category$_j$. A value of one assigned to all β_j implies equal potency among categories.

As currently configured for demonstration purposes, PMEX performs its calculations for individual user-specified population groups. At the user's discretion, groups may be distinguished by age and occupation or by susceptibility. It is anticipated that later model versions will sum exposure and inhaled dosage across groups to calculate community-wide aggregate exposure. It is this aggregate community-wide and susceptible group exposure that is most appropriate for use in evaluating control strategies. Susceptibility differences among groups could also be addressed in a manner similar to the use of potency weights, β_j, in eq 2.

Ambient PM Concentrations

Ambient PM concentrations are characterized in eqs 1 and 2 using monitoring data, apportioned among PM species categories by previous receptor modeling (although in the future, results of PM air quality modeling could instead be used). PM_{10} concentrations are used for purposes of testing the initial PMEX prototype, since $PM_{2.5}$ data have not yet been widely collected. However, the methodology proposed here is readily applicable to $PM_{2.5}$ when those data become available. Receptor modeling studies have apportioned monitored PM_{10} concentrations to different PM categories in a number of different areas of the country (see reference 3 for a summary). In PMEX, the N-hour average PM concentration for PM category$_j$ during hour$_i$ is expressed as

$$C_{N\text{-}hr\,ij} = CONC\{PM\ category_j, location_i\} \qquad (3)$$

where CONC is an array of $M \times L$ values that has an N-hour average concentration for each of M different PM categories for each of L possible exposure locations, and location$_i$ is the geographical location of the exposure during hour$_i$.

Each PM category has its own diurnal concentration profile, reflecting hourly variation in emission or atmospheric formation and by geographical location. A diurnal profile is an hourly sequence of weighting values such that their multiplication by the N-hour average concentration results in an N-hour sequence of hourly concentration values. An hourly weighting value represents the multiple or fraction of the N-hour average concentration $C_{N\text{-}hr\,ij}$ during hour$_i$ (for example, a value of 0.5 would mean that the concentration during hour$_i$ was half that of the N-hour average concentration). The weighting value for PM category$_j$ during hour$_i$ at location$_i$ is expressed as

$$\phi_{ij} = DIURNAL\{PM\ category_j, hour_i, location_i\} \qquad (4)$$

where DIURNAL is an array of $M \times 24 \times L$ dimensionless values for each of M different PM categories, 24 hr, and L possible exposure locations. For initial PMEX testing, hypothetical diurnal profiles have been developed. Primary motor vehicle exhaust, for example, is assumed to follow morning and evening commute patterns. Further refinement of profiles is expected in future work.

Indoor-Outdoor Ratios

Indoor-outdoor concentration differences are characterized by the indoor-outdoor ratio, calculated using data reported in other studies or PM indoor air quality modeling described elsewhere,[4–7] with ratio values dependent on building configuration and particle size. Five microenvironments are currently considered by the PMEX model: home, work, vehicle, near roadway, and outdoors. The indoor-outdoor ratio I/O_i at $hour_i$ is expressed as

$$I/O_i = INDOOR\{microenvironment_i\} \tag{5}$$

where INDOOR is a vector of indoor-outdoor ratios for each microenvironment, and $microenvironment_i$ is the microenvironment in which exposure takes place during $hour_i$.

Ventilation Rate

Physical exercise level is characterized by ventilation rate. The ventilation rate during $hour_i$ is expressed as

$$V_i = EXERCISE\{level_i\} \tag{6}$$

where EXERCISE is a vector of ventilation rates for each of a range of different exercise levels, and $level_i$ is the exercise level at which exposure takes place during $hour_i$. The model considers four exercise levels: resting, light, moderate, and heavy.

Source Class Mapping

The model calculates relative potency-weighted inhaled dosage D_j for each PM $category_j$ using eq 2. However, more than one source class may contribute to the inhaled dosage for a given PM category. To separate inhaled dosage by source class for greater convenience in control strategy design, inhaled dosage by PM category is mapped to inhaled dosage by source class. The PMEX model currently distinguishes five source classes: motor vehicles, power plants, other stationary (non-power plant), fugitive dust, and geological. Inhaled dosage (weighted by relative potency) by source class is expressed as

$$D_{source\ class_k} = \sum_{j=1}^{M} \alpha_{kj} D_j \tag{7}$$

where $D_{source\ class\ k}$ is inhaled dosage from $source\ class_k$, D_j is inhaled dosage for PM $category_j$, and α_{kj} is an array of mapping coefficients such that α_{kj} is the fractional contribution of the dosage from PM $category_j$ to the dosage from $source\ class_k$. Values of α_{kj} for a given source class sum to 1 across PM categories.

ILLUSTRATIVE EXAMPLE

The model described in this paper calculates PM exposure and relative potency-weighted inhaled dosage for several user-specified age-occupation or susceptible groups. While preliminary and solely for purposes of illustration, a hypothetical example is presented to demonstrate the feasibility of such calculations. Results comparing the relative contributions of different source classes calculated on the basis of relative potency-weighted inhaled dosage are presented for several different assumptions about the relative potency of PM_{10} species categories.

Input Data

Inhaled dosage is calculated in the example using PM_{10} concentrations measured in summer 1987 at the Rubidoux monitor, located in the eastern portion of California's South Coast Air Basin (SCAB, the Los Angeles area). Data input to the PMEX model are presented in Table 1. Concentrations measured on a high-PM_{10} day were apportioned to PM_{10} category by Watson et al.[8] using receptor modeling. The 24-hr PM_{10} concentrations reported by Watson et al. for each PM category are shown in Table 1a as the data input for Location 1. Since PM_{10} category concentrations were not reported for other locations, Location 2 concentrations input to the model are hypothetical, based on small, arbitrary variation in Location 1 concentrations. For the particular case shown in Table 1a, relative potencies are set to 1, implying that all PM_{10} species categories are assumed to be of equal potency.

Activity patterns are shown in Table 1c for two hypothetical persons, an adult and a child. Patterns consisting of hourly sequences of microenvironment, exercise level, and geographical location are specified for each person. While the activity patterns shown are for illustration purposes, statistically representative patterns based on actual time-diary survey data are available or can be developed for a range of different age-occupation or susceptible groups.

Indoor-outdoor ratios are specified in Table 1d for each of five microenvironments. For the home microenvironment, the I/O ratio (0.61) used is for a typical U.S. residence with the windows closed, and is based on indoor air quality modeling reported previously.[6,7] For the work microenvironment, the I/O ratio (0.37) is calculated using indoor air modeling and data typical of southern California office buildings with medium-to-high efficiency filters in heating, ventilation, and air conditioning (HVAC) systems. For vehicle and near roadway microenvironments, the I/O ratio should be interpreted as the ratio of local- to central-site monitor concentrations. Ambient PM_{10} concentrations input to PMEX are from central-site monitors. PM_{10} concentrations in vehicle and near roadway microenvironments, however, are typically higher than measured at central-site monitors, with the difference due to local motor vehicle emissions. Roadway PM_{10} levels can be on the order of twice or more the levels away from the roadway (see, for example, Reference 9). For these two microenvironments, then, the I/O ratio is set to 2.0 to adjust for differences between central-site and roadway concentrations.

(a) INPUT: Relative Potency and 24-hour Concentration Data

Monitor: Rubidoux, CA, summer 1987.

PM Category	Relative Potency	24-hour Concentration (μg/m3) Location 1		Location 2	
Primary Geological	1.0	34.9	30%	32.0	33%
Primary Construction	1.0	4.5	4%	4.8	5%
Primary Motor Vehicle Exhaust	1.0	17.3	15%	18.0	18%
Secondary Ammonium Sulfate	1.0	9.5	8%	9.5	10%
Secondary Ammonium Nitrate	1.0	27.4	24%	28.4	29%
Other	1.0	21.2	18%	4.9	5%
Total		114.8		97.6	

(b) INPUT: Source Class Apportionment

	PM Category	Off-Road Vehicles	On-Road Vehicles	Stationary	Fugitive Dust	Geological	Total
1	Primary Geological					100%	100%
2	Primary Construction				100%		100%
3	Primary Motor Vehicle Exhaust	36%	64%				100%
4	Secondary Ammonium Sulfate	39%	32%	29%			100%
5	Secondary Ammonium Nitrate	21%	66%	13%			100%
6	Other	20%	35%	45%			100%

(c) INPUT: Activity Patterns —Microenvironment, Exercise Level, and Location

	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Person 1	Microenvironment	1	1	1	1	1	1	1	1	3	2	2	2	2	2	2	2	2	3	1	1	1	1	1	1
	Exercise Level	1	1	1	1	1	1	1	2	2	2	3	2	2	2	3	2	2	2	2	2	1	1	1	1
	Location	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1
Person 2	Microenvironment	1	1	1	1	1	1	1	1	3	2	2	2	2	2	2	3	5	5	1	1	1	1	1	1
	Exercise Level	1	1	1	1	1	1	1	2	2	2	4	2	3	2	4	2	4	3	2	2	1	1	1	1
	Location	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

(d) INPUT: Indoor-Outdoor Ratios

	Microenvironment	I/O Ratio
1	Home	0.61
2	Work	0.37
3	Vehicle	2.00
4	Near Roadway	2.00
5	Outdoor	1.00

(e) INPUT: Exercise Levels

	Level	Ventilation Rate (L/min)
1	Resting	5.0
2	Light	16.7
3	Moderate	20.0
4	Heavy	31.7

Table 1. Example input data to PMEX model (Los Angeles).

Finally, for the outdoor microenvironment, the I/O ratio is 1.0 by definition.

Ventilation rates are specified in Table 1e for resting, light, moderate, and heavy exercise using values in EPA's *Exposure Factors Handbook*.[10] Inhaled dosage by PM_{10} category is apportioned to source class using the mapping in Table 1b. Primary geological and primary construction categories map uniquely to geological and fugitive dust source classes. Category apportionment to the other source classes is based on an area-wide emission inventory. In the example, a 1993 emissions inventory developed for the SCAB by the South Coast Air Quality Management District is used.[11] Primary motor vehicle exhaust is divided between on-road and off-road vehicle classes in proportion to area-wide mobile source PM_{10} emissions for the two classes. Secondary PM_{10} is related to primary and precursor emissions only in highly complex ways, with analysis of atmospheric formation and transport requiring air quality modeling to address properly. Future work will eventually involve source apportionment based on such air quality modeling. However, for the limited demonstration purposes here, secondary ammonium sulfate is assumed to be apportioned among on-road vehicles, off-road vehicles, and stationary sources in rough proportion to sulfur dioxide emissions from the three classes in available emission inventories. Secondary ammonium nitrate is assumed to be related to the same three source classes in approximate proportion to nitrogen oxide emissions.

Preliminary Results

The PMEX model is used to calculate relative potency-weighted PM_{10} inhaled dosage for each hour during the 24-hr simulation period. Calculated hourly values are shown in Figure 1 for different PM categories.

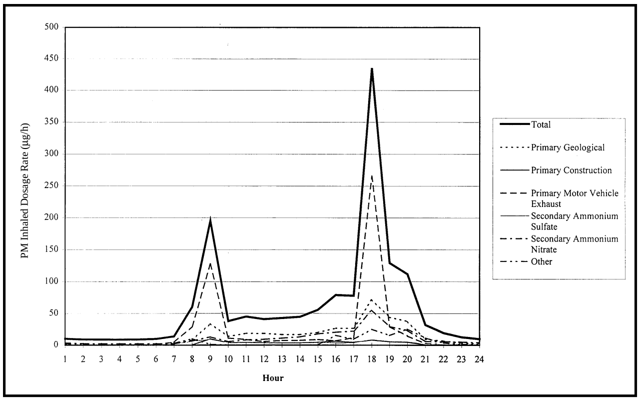

Figure 1. Hourly inhaled dosage by PM_{10} category, Los Angeles (adult, equal PM_{10} category potency).

A hypothetical individual is considered who is assumed to exhibit a pattern of activity characteristic of an adult. All PM_{10} species categories are assumed to be equally potent. Two distinct peaks are evident, primarily due to higher motor vehicle emissions during the morning and evening rush hours. The magnitudes of the peaks result from the combination of rush-hour emissions and the individual being in a vehicle or near a roadway, outdoors a portion of the time, and at a higher exercise level.

Inhaled dosage integrated over the full 24-hr simulation period is shown in Figure 2 , split among PM_{10} categories. Primary motor vehicle exhaust (37%) is the largest contributor, followed by primary geological (26%) and secondary ammonium nitrate (18%). Inhaled dosage by PM_{10} source class is presented in Figure 3. On-road motor vehicles (41%) contribute the greatest amount, followed by geological (26%) and off-road motor vehicles (21%).

The sensitivity of source class contribution to PM_{10} inhaled dosage is shown in Figure 4 for several different assumptions about the relative potency of PM_{10} categories. Results are compared for four cases. For reference, apportionment among source classes based on ambient PM_{10} concentration is shown in the leftmost bar for each source class. In Case 1 (equal potency), all relative potencies are set to 1, that is, all PM_{10} categories are assumed to be of equal potency. The relative contribution of on- and off-road vehicles based on inhaled dosage increases over that based on ambient. The stationary source contribution drops nearly in half, from 14% to 8%.

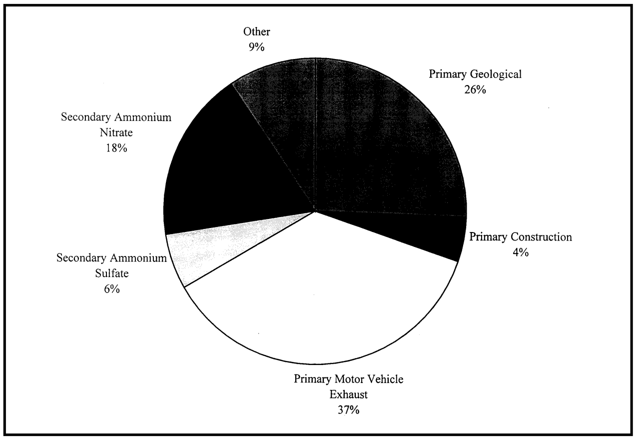

Figure 2. Inhaled dosage by PM_{10} category, Los Angeles (adult, equal PM_{10} category potency).

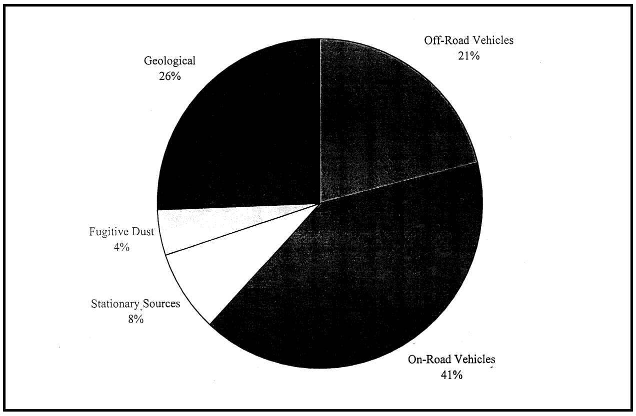

Figure 3. Inhaled dosage by PM_{10} source class, Los Angeles (adult, equal PM_{10} category potency).

New research is under way to investigate whether different PM species exhibit different health potencies. To allow for the possibility that such differences may be found in the future, Cases 2, 3, and 4 test the sensitivity of source class apportionment to different assumptions about the relative potencies of PM_{10} categories. Inhaled dosage for each category is weighted by potency as follows:

- Case 2 (Geo = 0.1)—geological dust is arbitrarily assumed to be one-tenth the potency of the other categories;
- Case 3 (NO_3 = 0.1)—ammonium nitrate is assumed to be one-tenth as potent as the others; and
- Case 4 (MV Exh = 0.1)—motor vehicle exhaust is assumed to be one-tenth as potent.

As shown in Figure 4, a lower potency for geological dust would increase the relative contribution of on- and off-road vehicles by about 40%, decrease the contribution of stationary sources by about 20%, and decrease the contribution of fugitive dust and geological sources significantly.

SUMMARY

This paper proposes that control strategies to attain the new federal PM standards be designed to minimize community and susceptible group exposure to, and the inhaled dosage of, that portion of ambient PM believed to contain the species of health concern. Properly done, such minimization is equivalent to maximization of human health risk reduction. Implementation of such a principle is illustrated using an initial prototype of the PMEX model. PMEX

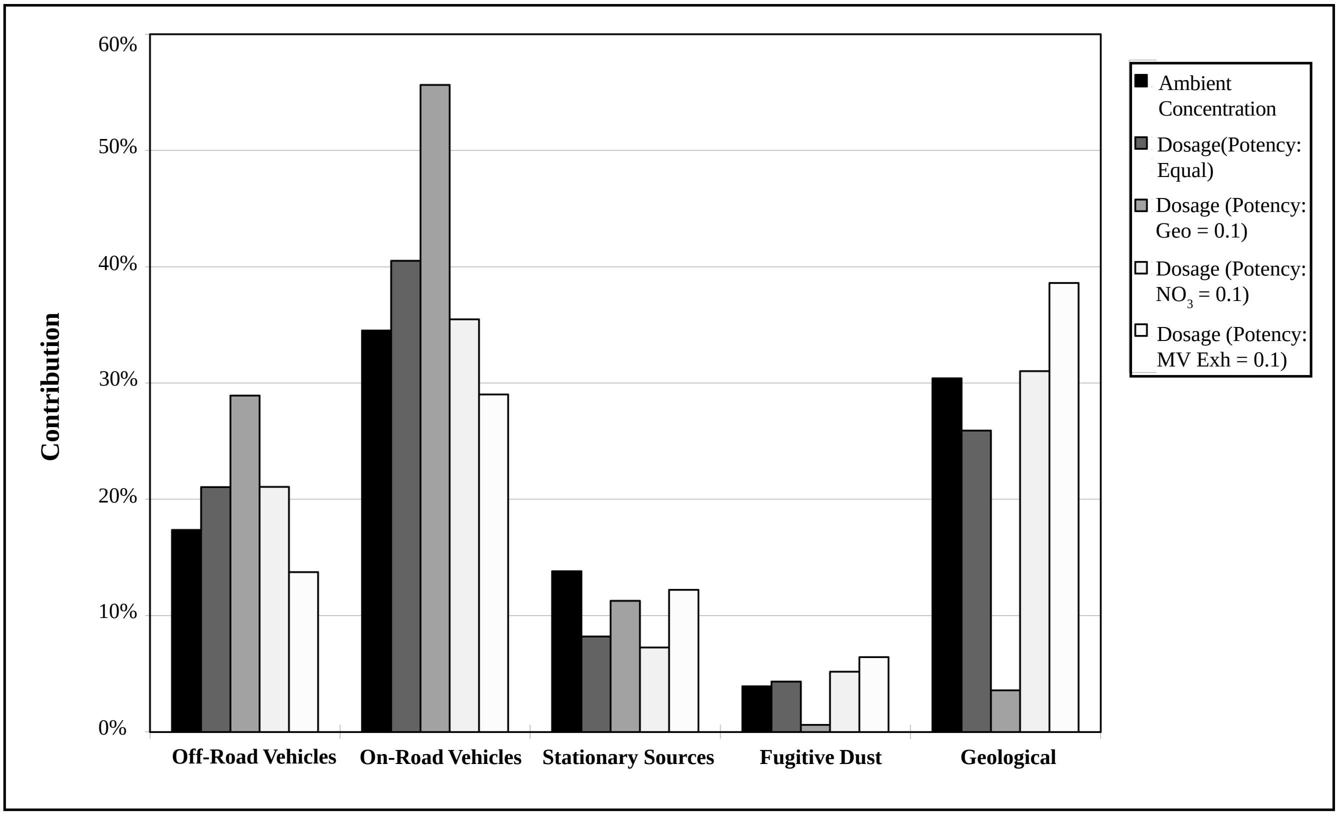

Figure 4. PM$_{10}$ source class contributions for different assumed PM$_{10}$ category potencies (adult), Los Angeles.

calculates PM exposure and relative potency-weighted inhaled dosage, accounting for age-occupation or susceptible group activity patterns, indoor-outdoor differences, and geographical location. It is anticipated that later versions of the model will calculate aggregate exposure and inhaled dosage across the community and susceptible groups as figures-of-merit for control strategy optimization.

Modeling results are presented for a hypothetical example, in which relative potency-weighted inhaled dosage is apportioned among different source categories for different assumptions about relative PM$_{10}$ species potency. Results, while preliminary, demonstrate that calculation of PM exposure and inhaled dosage is feasible, and conclusions about source class contribution can be appreciably different based on inhaled dosage rather than based on ambient air measurements or emission inventories.

REFERENCES

1. *National Ambient Air Quality Standards for Particulate Matter (Final Rule)*; 62 FR 38651; July 18, 1997.
2. *Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information (Staff Paper)*; U.S. Environmental Protection Agency: Research Triangle Park, NC, July 1996; EPA-452/R-96-013.
3. *Air Quality Criteria for Particulate Matter (Criteria Document)*; U.S. Environmental Protection Agency: Research Triangle Park, NC, April 1996; EPA/600/P-95-001aF through EPA/600/P-95-001cF.
4. Hayes, S.; Wilhelmi, J.; Pye, S.; Gates, L.; Levin, L. "Development of a modeling methodology for assessing exposure to acidic aerosols and gases," Presented at the 86th Annual Meeting & Exhibition of the Air & Waste Management Association, Denver, CO, June 1993.
5. Hayes, S.; Pye, S.; Levin, L. "Sensitivity analysis of a Monte Carlo exposure assessment model for acidic aerosols and gases," Presented at the 87th Annual Meeting & Exhibition of the Air & Waste Management Association, Cincinnati, OH, June 1994.
6. Hayes, S.; Stuart, A.; Pye, S.; Levin, L.; Killus, J. "Assessing exposure to airborne particulate matter," Presented at the 89th Annual Meeting & Exhibition of the Air & Waste Management Association, Nashville, TN, June 1996.
7. Hayes, S.; Pye, S. "Exposure and health risk considerations in setting new U.S. particulate standards," Presented at the 90th Annual Meeting & Exhibition of the Air & Waste Management Association, Toronto, Ontario, Canada, June 1997.
8. Watson, J.G.; Chow, J.C.; Lowenthal, L.C.; Pritchett, C.A.; Frazier, C.A.; Neuroth, G.R.; Robbins, R. "Differences in the carbon composition of source profiles for diesel- and gasoline-powered vehicles," *Atmos. Environ.* **1994**, *28*, 2493–2505.
9. *Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant, Part A, Exposure Assessment (Draft)*; California Air Resources Board: Sacramento, CA, May 1997.
10. *Exposure Factors Handbook, Volume I of II, General Factors (SAB Review Draft)*; U.S. Environmental Protection Agency: Washington, DC, August 1996; EPA/600/P-95/002Ba.
11. *1997 Air Quality Management Plan*; South Coast Air Quality Management District: Diamond Bar, CA, 1997.

About the Authors
Stanley R. Hayes is a principal with ENVIRON International Corporation, 6001 Shellmound St., Ste. 700, Emeryville, CA 94608. Julian D. Marshall, previously with ENVIRON, is currently a lecturer and an international fellow at Temasek Polytechnic in Singapore.