Effectiveness and Cost of Reducing Particle-Related Mortality with Particle Filtration

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ABSTRACT
This paper evaluates the mortality-related benefits and costs of improvements in particle filtration in U.S. homes and commercial buildings based on models with empirical inputs. The models account for time spent in various environments as well as activity levels and associated breathing rates. The scenarios evaluated include improvements in filter efficiencies in both forced air heating and cooling systems of homes and heating, ventilating, and air conditioning systems of workplaces as well as use of portable air cleaners in homes. The predicted reductions in mortality range from approximately 0.25 to 2.4 per 10,000 population. The largest reductions in mortality were from interventions with continuously operating portable air cleaners in homes because, given our scenarios, these portable air cleaners with HEPA filters most reduced particle exposures. For some interventions, predicted annual mortality-related economic benefits exceed $1000 per person. Economic benefits always exceed costs with benefit-to-cost ratios ranging from approximately 3.9 to 133. Restricting interventions to homes of the elderly further increases the mortality reductions per unit population and the benefit-to-cost ratios.
Keywords: benefits, costs, health, filtration, mortality, particles

Practical implications.
The high benefit-to-cost ratios for the filtration interventions suggest routine use of higher efficiency filters in home forced air heating and cooling systems and in commercial building heating, ventilating, and air conditioning systems. The findings also suggest that upgrades be made to the associated minimum filtration efficiency requirements in standards for building ventilation and indoor air quality. Also, home owners may want to continuously operate portable air cleaners with high efficiency filters in their homes, particularly if occupants are elderly with increased susceptibility to particle-related health effects.

1.0 INTRODUCTION
Many studies have documented substantial mortality and morbidity associated with particulate pollution in outdoor air [1-5]. Globally, in 2010, an estimated 3.2 (2.8 – 3.6) million premature deaths were attributable to particles in outdoor air. Among outdoor air pollutants, particles are the largest source of mortality [4]. To reduce the adverse health effects of particles, many developed countries have dedicated much effort to reduce both primary sources of particles and sources of reactive gaseous pollutants that form particles in the atmosphere. These mitigation efforts have, in many cases, been highly effective. For example, the U.S. Environmental Protection Agency [5] has estimated that mitigation measures implemented as a result of the Clean Air Act (CAA) will prevent 230,000 (45,000 – 490,000) particle-related premature deaths in the U.S. in 2020, plus 7,000 premature deaths from ozone. The associated estimated monetary benefits from reduced particle-related mortality in 2020 were $1.7 trillion ($0.17 trillion to $5.3 trillion) U.S. dollars (year 2006 dollars). The cost of air pollution mitigation efforts in 2020 attributable to the CAA was estimated to be $65 billion, yielding a benefit cost ratio of 26, considering only particle-related mortality benefits. This benefit cost ratio increases to 31 when all benefits are counted. Nearly all of the mitigation measures implemented as a result of the CAA contributed to reductions in outdoor air particles, but many measures also

reduced outdoor air concentrations of other air pollutants. Per prevented particle-caused premature death, the annual cost of CAA measures in 2020 is $280,000.

From the prior discussion of the CAA, traditional air pollution control measures can be highly effective and cost effective in reducing particle-related mortality. Nevertheless, the adverse health consequences of particles remain substantial and other control options deserve consideration. People in the U.S. and in similar countries are indoors approximately 90% of the time [6, 7]. Accounting for time spent indoors, indoor concentrations of particles of outdoor air origin, and breathing rates, Fisk [8] estimated that about 65% of inhalation of outdoor air particles occurs when people are indoors. Given the importance of indoor exposures to particles from outdoor air, improvements in particle filtration systems in buildings can be expected to reduce these exposures and to reduce associated premature mortality and morbidity. A number of studies have evaluated scenarios of improved filtration using mass balance models to predict how filtration affects indoor concentrations of particles of outdoor air origin together with concentration-response equations from epidemiological research to relate particle concentrations with mortality. The following paragraphs summarize scenarios assessed and findings.

Beko, Clausen [9] modeled a hypothetical office building with and without a medium-efficiency filter in the supplied outdoor air. No indoor air recirculated through filters. The outdoor air concentration of particles less than 10 µm in diameter was assumed to equal 30 µg m^{-3}. The annual per-occupant cost of filtration was estimated to be $2.64. The projected annual per-occupant economic benefits, based on the product of reduced years of lost life and $457,000 per year of lost life, were much higher -- approximately $45, $90, and $135, assuming that the filtration reduced indoor particle concentrations by 30%, 60%, and 90%. Macintosh, Minegishi [10] modeled the use of high efficiency electronic filtration systems in place of conventional filters in the forced air heating and cooling (HAC) systems of 1.04 million homes with 2.7 million occupants in Ohio. They assumed that the forced air systems operated continuously at 50% of their typical air flow rates, even when heating and cooling was not necessary. They estimated that the filtration intervention would reduce indoor concentrations of particles of outdoor-air origin less than 2.5 µm in diameter ($PM_{2.5}$) by approximately two thirds and would prevent 700 premature deaths per year, corresponding to a 3.7% decrease in the annual mortality risk.

Montgomery, Reynolds [11] modeled morbidity and mortality-related monetary benefits and costs for filtration in a hypothetical office building with filters in the outdoor air supply system with no air recirculation through filters. The modeling considered a range of filter efficiencies and several cities from around the world and accounted for filter costs and filtration energy costs. The predicted annual cost per occupant of using filters with a MERV 13 efficiency rating varied from about $7.5 to $27, with the higher costs in locations with higher particle concentrations. Health-related monetary benefits far exceeded filtration costs, e.g., by a factor of ten. The net economic benefit of filtration increased with filter efficiency rating, with a leveling off as the filter efficiency rating exceeded about MERV 15. Net benefits were higher in cities with highly elevated outdoor $PM_{2.5}$concentrations and peaked at about U.S. $800 per

occupant. Supplemental calculations for office buildings in London with HVAC systems that supply outdoor and recirculated indoor air indicated benefit to cost ratios increasing with filter efficiency rating from MERV 7 to MERV 15.

Zhao, Azimi [12] modeled use of filters with a range of efficiency ratings from MERV 5 to HEPA (essentially 100% efficient) in the forced air heating and cooling systems of homes in 22 US cities. Various home vintages (old, existing, and new) with different levels of air tightness and air infiltration were modeled. Some modeling considered homes with three types of mechanical outdoor air ventilation. Filtration costs were not estimated. Here we summarize only their predictions for homes without mechanical outdoor air ventilation. For their category of "old homes", the predicted ratio of indoor-to-outdoor concentration of $PM_{2.5}$ from outdoor air decreased with increased filter efficiency rating from about 0.38 with a MERV 5 filter to 0.23 with a HEPA filter. For their category of "existing homes", more recently built than old homes, the corresponding predicted ratios were 0.18 to 0.14. For "new homes", the predicted ratio was approximately 0.02 to 0.01. As filter efficiency increased above MERV 5 (the reference), predicted mortality rates diminished. For old homes, the maximum reduction in mortality was about 1.7% when a HEPA filter was used. For existing homes the maximum mortality decrease was about 0.6%, for new homes predicted mortality decreases were very small due to the very low predicted indoor concentrations of particles from outdoors. The estimated monetary benefits of increasing filter efficiency above the based-case MERV 5 efficiency varied among home vintages and among cities, partly because of different outdoor particle concentrations. With a prevented premature death valued at $7.2 million, for old homes annual monetary benefits per person peaked at approximately $1300. For existing homes, the peak per person benefit was approximately $500.

Zuraimi and Tan [13] modeled the reductions in mortality in Toronto, Canada from replacing standard furnace filters with MERV 15 rated filters in homes constructed to the latest energy efficiency standards. They predicted a 19% reduction in $PM_{2.5}$ exposures in summer and a 28% reduction in winter, with a reduction in non-accident mortality of 26%. They also predicted similar magnitude decreases in chronic bronchitis, hospitalization, and restricted activity days.

This paper further evaluates the mortality-related benefits of filtration along with filtration costs, and compares costs with benefits. The scenarios evaluated and calculation methods differ from those in prior analyses. The scenarios include improvements in filter efficiencies in HAC systems of homes and in the heating, ventilating, and air conditioning (HVAC) systems of commercial buildings as well as use of portable air cleaners in homes. The modeling uses measured seasonal-average ventilation rates of homes, which reflect window opening. The models account for time spent in various environments (e.g., home, work, outdoors, vehicles) as well as activity levels and associated breathing rates. Costs of preventing particle-related mortality with filtration are compared with the cost of implementing the CAA.

2.0 METHODS

2.1 Overview

The potential reductions in mortality from various improvements in particle filtration in U.S. single family homes (defined here as homes in buildings with one home per building) and in workplaces and other non-residential buildings is evaluated. The homes are assumed to have no mechanical systems providing ventilation with outdoor air, which is typically the case in existing U.S. homes. Mechanical ventilation of homes has only been required in recent years and only in some regions of the U.S. [14]. Indoor air concentrations of $PM_{2.5}$ of outdoor air origin (hereinafter simply referred to as $PM_{2.5}$ concentrations) are estimated with steady state mass balance models with inputs based on empirical data. Indoor concentrations of $PM_{2.5}$ are predicted with and without improvements in filtration. The $PM_{2.5}$ concentrations are used together with time-activity data and breathing rate data to estimate how much the filtration interventions reduced total indoor and outdoor inhalation intake of $PM_{2.5}$. These results are used to estimate the reductions in outdoor air $PM_{2.5}$ concentrations that would reduce total $PM_{2.5}$ inhalation as much as the filtration interventions, then, reductions in mortality are estimated with concentration response equations based on epidemiologic data and outdoor $PM_{2.5}$ concentrations. Filtration costs are also estimated. Calculations are performed for three locations [Los Angeles CA (Los Angeles County), Elizabeth NJ (Union County), and Houston TX (Harris County)] where data on air-exchange rates exist. We selected these cities because of the available data for these locations on home ventilation rates per season. The climates in these cities span much of the range in the US, with Los Angeles having a mild dry climate, Elizabeth having cold winters and hot summers, and Houston having hot humid weather. We performed calculations for each season using seasonal-level central estimates and measures of variance for parameters that vary seasonally such as $PM_{2.5}$ concentration and ventilation rate.

2.2 Interventions

Table 1 summarizes the baseline (B1 and B2) and intervention (i1 – i9) conditions. In B1, the home has a forced air heating and cooling (HAC) system with airflow only when there is a need for heating and cooling and with a typical low efficiency particle filter. In B2, the home has no forced-air HAC system and no particle filtration. Interventions i1 and i2 increase filtration by the home HAC systems via increases in operation time of the HAC fan, with an increase in the system's filter efficiency in i2. Intervention i3 increases the efficiency of the filter in the HAC system with no increase in operation time. Interventions i4 – i6 combine these measures with use of a continuously operating portable air cleaner in the home. The air cleaner has a clean air delivery rate, essentially a product of air flow rate and $PM_{2.5}$ removal efficiency, equivalent to 1.2 indoor air volumes per hour; however, because portable air cleaners tend to preferentially clean nearby air, i.e., the indoor air is not perfectly mixed, we assume an effective clean air delivery rate of 1.0 indoor volumes per hour (see supporting information). In i7, a portable air cleaner is added to a home without a HAC system. Intervention i7, is the only intervention that uses baseline B2 as the reference. In interventions i8 and i9, the efficiency of filters used in the HVAC systems of commercial and institutional buildings is improved.

Table 1. Baseline and intervention conditions.

Baseline or Intervention code	Reference Condition	Conditions			
		Forced Air System Operation in Home	Efficiency of Filter in Home Forced Air System	Continuously Operating Portable Air Cleaner with HEPA Filter in Home	Efficiency of filters in HVAC systems of other buildings
B1	NA	Intermittent[A]	MERV 6	No	MERV 8
B2	NA	No forced air	NA	No	MERV 8
i1a i1b	B1	30% time[B] 40% time[C]	MERV 6	No	MERV 8
i2a i2b	B1	30% time[B] 40% time[C]	MERV 9	No	MERV 8
i3	B1	Intermittent[A]	MERV 9	No	MERV 8
i4	B1	Intermittent[A]	MERV 6	Yes	MERV 8
i5a i5b	B1	30% time[B] 40% time[C]	MERV 6	Yes	MERV 8
i6a i6b	B1	30% time[B] 40% time[C]	MERV 9	Yes	MERV 8
i7	B2	No forced air	NA	Yes	MERV 8
i8	B1	Intermittent[A]	MERV 6	No	MERV 11
i9	B1	Intermittent[A]	MERV 6	No	MERV 13

[A]as needed for heating and cooling, typically on the order of 15% to 20% of the time
[B]30% time, or greater if needed for heating and cooling [C]40% time, or greater if needed for heating and cooling

2.3 Mass balance and mortality modeling

Analyses were performed using the model of Fisk and Chan [15] which enables prediction of changes in $PM_{2.5}$ total inhalation intake as a function of the efficiency of filters used in homes and other buildings, operation times of home HAC systems, and characteristics of portable air filtration systems. Indoor air $PM_{2.5}$ concentrations are calculated using steady-state mass balance equations for spaces with well mixed indoor. The model is for a home with well mixed air; however, as discussed previously the particle removal of the air cleaner has been discounted to account for imperfect mixing. These equations relate indoor $PM_{2.5}$ concentrations to outdoor concentrations. For the baseline condition houses

$$C_{B1} = K_{B1}\, C_O \quad (1)$$
$$C_{B2} = K_{B2}\, C_O \quad (2)$$
$$K_{B1} = P\, \lambda_V / (\lambda_V + \lambda_D + \lambda_F) \quad (3)$$
$$K_{B2} = P\, \lambda_V / (\lambda_V + \lambda_D) \quad (4)$$

where C_{B1} and C_{B2} are the indoor $PM_{2.5}$ concentrations in baseline cases B1 and B2 without any interventions, C_o is the $PM_{2.5}$ concentration in outdoor air, P is the particle penetration factor, i.e., the fraction of particles that penetrate through the building envelope during air infiltration (dimensionless), λ_V is the infiltration ventilation rate, λ_D is the rate of particle removal by deposition on indoor surfaces, and λ_F is the rate of particle removal by the home's forced air heating and air conditioning system in the absence of an intervention. In these and subsequent equations, particle concentration are in units of μg m^{-3}, and all λ parameters are normalized by the indoor volume and have units of h^{-1}. The parameter λ_F is calculated from equation 5

$$\lambda_F = Q\, D\, \varepsilon_L \quad (5)$$

where Q is the air flow rate of the forced air heating and air conditioning system divided by the indoor volume, D is the fraction of time that the forced air fan operates, sometimes called the duty cycle, and ε_L is the $PM_{2.5}$ removal efficiency of the low efficiency filter normally used in the forced air system, i.e., unaffected by an intervention.

We assume that buildings other than homes (commercial buildings) typically have air infiltration plus continuous mechanical outdoor air ventilation and indoor air recirculation, with the incoming outdoor air and recirculated air passing through a particle filter. Under these conditions, the mass balance equation for the indoor concentrations of particles is

$$C_W = K_W C_O \tag{6}$$

with

$$K_W = ((1 - \varepsilon_W)\lambda_{MW} + \lambda_{IW} P)/(\lambda_{IW} + \lambda_{MW} + \lambda_{DW} + \varepsilon_W \lambda_{RW}) \tag{7}$$

where C_W is the indoor concentration at work, school, or other indoor non-residential locations, ε_W is the $PM_{2.5}$ removal efficiency of the particle filter, λ_{MW} is the flow rate of outdoor air supplied mechanically, λ_{IW} is the air infiltration rate, λ_{DW} is the particle deposition rate in buildings other than homes, and λ_{RW} is the mechanical recirculation air flow rate.

The particle concentration in vehicles (C_V), needed to estimate total particle inhalation intake, is estimated as a fraction of the outdoor air concentration, i.e.,

$$C_V = K_V C_O \tag{8}$$

with K_V based on empirical data.

For intervention cases i1-i9, the residential indoor particle concentrations C_N are calculated as follows

$$C_N = K_N C_o \quad \text{for N = 1 – 9} \tag{9}$$

$$K_N = P \lambda_V / (\lambda_V + \lambda_D + \lambda_N) \quad \text{for N = 1 to 9} \tag{10}$$

with λ_N, for N = 1 to 9, equal to the rates of particle removal by residential filtration during interventions i1 through i9, respectively. Values of λ_N are calculated as follows

$$\lambda_1 = D_1 Q \ \varepsilon_L \tag{11}$$

$$\lambda_2 = D_2 Q \ \varepsilon_H \tag{12}$$

$$\lambda_3 = D_3 Q \ \varepsilon_H \tag{13}$$

$$\lambda_4 = D_4 Q \ \varepsilon_L + Q_P \ \varepsilon_P \tag{14}$$

$$\lambda_5 = D_5 Q \ \varepsilon_L + Q_P \ \varepsilon_P \tag{15}$$

$$\lambda_6 = D_6 Q \ \varepsilon_H + Q_P \ \varepsilon_P \tag{16}$$

$$\lambda_7 = Q_P \ \varepsilon_P \tag{17}$$

$$\lambda_8 = D_8 Q \ \varepsilon_L \tag{18}$$

$$\lambda_9 = D_9 Q \ \varepsilon_L \tag{19}$$

where ε_H is the $PM_{2.5}$ removal efficiency of the higher efficiency filter in the residential forced air system during interventions i2, i3, and i6, Q is the air flow rate in the forced air heating and cooling system divided by the indoor volume, Q_p is the air flow rate of the portable air cleaning system divided by indoor volume, and ε_p is the $PM_{2.5}$ removal efficiency of the portable air cleaner. For interventions i1a, i2a, i5a, and i6a, the duty cycle D is set to 0.3 when it is otherwise less than 0.3. For interventions i1b, i2b, i5b, and i6b, the duty cycle D is set to 0.4 when it is otherwise less than 0.4. For interventions i3, i4, i8, and i9, the duty cycle D is as needed for space heating and cooling.

For the intervention cases i8 and i9 with improved filtration in other buildings, ε_W is revised in equation (7) to reflect the particle removal efficiency of medium and high efficiency filters, to give K_{WN} for N=8 and 9.

Rates of $PM_{2.5}$ inhalation intake are calculated as follows

$$I_{B1} = C_O(B_O\, T_O + B_S\, K_{B1}\, T_S + B_{HA}K_{B1}T_{HA} + B_W K_W T_W + B_V\, K_V\, T_V) \quad (20)$$

$$I_{B2} = C_O(B_O\, T_O + B_S\, K_{B2}T_S + B_{HA}K_{B2}T_{HA} + B_W K_W T_W + B_V\, K_V\, T_V) \quad (21)$$

$$I_N = C_O\,(B_O\, T_O + B_S K_N\, T_S + B_{HA}K_N T_{HA} + B_W K_W T_W + B_V\, K_V\, T_V) \quad \text{for N = 1 to 7} \quad (22a)$$

$$I_N = C_O\,(B_O\, T_O + B_S K_{B1}\, T_S + B_{HA}K_{B1} T_{HA} + B_W K_{WN} T_W + B_V\, K_V\, T_V) \quad \text{for N=8 and 9} \quad (22b)$$

where: I_{B1} and I_{B2} are the $PM_{2.5}$ intake for baseline conditions B1 and B2; I_N is the $PM_{2.5}$ intake for intervention *N*; B_O, B_S, B_{HA}, B_W, B_V are inhalation rates when outdoors, at home asleep, at home awake, at work and other indoor locations, and in vehicles; and T_O, T_S, T_{HA}, T_W, and T_V are the times spent in the same environments.

Because mortality has been related to $PM_{2.5}$ concentrations in outdoor air, to estimate the health benefits of interventions we calculate effective $PM_{2.5}$ concentrations in outdoor air, designated C_{OE}, that produce intake rates for $PM_{2.5}$ equal to I_N. For interventions i1 – i6

$$C_{OE} = \frac{C_O\,(B_O\, T_O + B_S\, K_N\, T_S + B_{HA}\, K_N\, T_{HA} + B_W\, K_W\, T_W + B_V\, K_V\, T_V)}{(B_O\, T_O + B_S\, K_{B1}\, T_S + B_{HA}\, K_{B1}\, T_{HA} + B_W\, K_W\, T_W + B_V\, K_V\, T_V)} \quad \text{for N = 1 to 6} \quad (23)$$

and for intervention i7

$$C_{OE} = \frac{C_O\,(B_O\, T_O + B_S\, K_7\, T_S + B_{HA}\, K_7\, T_{HA} + B_W\, K_W\, T_W + B_V\, K_V\, T_V)}{(B_O\, T_O + B_S\, K_{B2}\, T_S + B_{HA}\, K_{B2}\, T_{HA} + B_W\, K_W\, T_W + B_V\, K_V\, T_V)} \quad \text{for N = 7} \quad (24)$$

and for interventions i8 and i9

$$C_{OE} = \frac{C_O\,(B_O\, T_O + B_S\, K_{B1}\, T_S + B_{HA}\, K_{B1}\, T_{HA} + B_W\, K_{WN}\, T_W + B_V\, K_V\, T_V)}{(B_O\, T_O + B_S\, K_{B1}\, T_S + B_{HA}\, K_{B1}\, T_{HA} + B_W\, K_W\, T_W + B_V\, K_V\, T_V)} \quad \text{for N=8, 9} \quad (25)$$

The derivations of equations 23 and 24 are provided by [15].
Changes in mortality risk are estimated via the equation [16]

$$\frac{\Delta y_i}{y_0} = -[\exp(-\beta\,(\Delta PM_{2.5}) - 1] \quad (26)$$

where $\Delta y_i/y_o$ is the fractional change in total mortality, β is the risk coefficient, and $\Delta PM_{2.5}$ is the change in outdoor air $PM_{2.5}$ concentration in micrograms per cubic meter corresponding to the change in total $PM_{2.5}$ inhalation intake due to the filtration intervention. Note that for interventions i8 and i9 in commercial buildings, equation 26 provides the average change in mortality risk for the full population of residents living in single family homes considered by baseline cases B1 and B2. The fractional reduction in mortality risk would be larger for the subpopulation spending much more than average time in commercial buildings. Prevented premature deaths (*PD*) are estimated with equation 27

$$PD = \frac{\Delta y_i}{y_0}(y_0) N_H O_H \tag{27}$$

with y_0 the baseline mortality rate, N_H is the number of homes, and O_H is the average number of occupants per home. The economic value of prevented deaths was obtained by multiplying PD by the unit value of a prevented premature death for year 2011.

2.4 Cost analysis

To estimate intervention costs we consider: 1) the incremental spending for high efficiency versus standard low efficiency filters in home HAC systems and commercial HVAC systems; 2) the cost of extra operation time of the home HAC fan in interventions i1, i2, i5, and i6; 3) the costs of portable air cleaners and periodically replacing their filters; 4) the costs of energy used by portable air cleaners; and 5) as discussed subsequently, the potential changes in energy use of home HAC systems and commercial building HVAC systems when higher efficiency filters are utilized. We assume that the labor cost for periodically replacing filters does not differ significantly between baseline and intervention cases.

We assume that the low efficiency filters in home HAC systems are changed three times per year and, to be conservative, that the high efficiency filters are changed four times per year [17]. For homes, the annual incremental cost per person of purchasing higher efficiency filters, CST_P, is

$$CST_P = (4\,P_H - 3\,P_L)/O_H \tag{28}$$

where P_H is the price of the higher efficiency filter, P_L is the price of the lower efficiency filter, and O_H is the number of occupants per home.

For interventions i1a, i2a, i5a, and i6a, the home HAC system fan is forced to operate 30% of the time, whenever the operation time necessary solely for space heating and cooling is less. The associated incremental electricity cost per house is

$$E_{HAC} = G_E(0.3 - D_{HC})\,Q\,V Z_{HAC}\,T \qquad \text{if } 0.3 > D_{HC} \tag{29a}$$
$$E_{HAC} = 0 \qquad \text{if } 0.3 \leq D_{HC} \tag{29b}$$

where G_E is the electricity price, D_{HC} is the duty cycle of the HAC system for space heating and cooling, Q is the HAC system air flow rate per unit indoor volume, V is the house volume, Z_{HAC} is

the power consumption of the HAC fan per unit airflow, and T is the elapsed time in hours. For interventions i1b, i2b, i5b, and i6b the calculations are analogous with 0.3 replaced by 0.4.

For portable air cleaners, assumed to operate continuously, the annual cost, CST_{AC}, per house is calculated per equation 30

$$CST_{AC} = 0.2\, E_P + E_{RF} + Q_P\, V\ \ Z_P\, G_E\ \ N \tag{30}$$

where E_p is the purchase price of the air cleaner, E_{RF} is the annual cost of replacement filters, Q_P is the air cleaner flow rate in indoor air volumes per unit time, V is the house volume, Z_P is the air cleaner's power consumption per unit clean air delivery rate, G_E is the residential electricity price, and N is the time of air cleaner operation per year. Implicit is equation 30 is an assumption that the air cleaner has a five year life. Two air cleaners were considered. The Brand X air cleaner has a HEPA filter replaced twice per year (twice the manufacturer's recommended frequency) plus prefilters replaced each three months; thus, the annual filter cost accounts for three replacements of the prefilter and one replacement of the HEPA filter in year 1 and four replacements of the prefilter plus two replacements of the HEPA filter each subsequent year. The Brand Y air cleaner has a washable prefilter and recommends annual filter replacement; however, we assume that filters are replaced twice per year. The supporting information includes text explaining why we assume more frequent filter replacement than recommended by manufacturers. The costs of filtration per house from equations 28 – 30 can be divided by the occupants per house to obtain costs per person.

Based on the discussion provided by Fisk and Chan [15], we assume that the upgrades in the efficiency of filters in HAC systems of homes does not significantly affect HAC energy consumption. For intervention i9 which replaces MERV 8 filters in commercial building with MERV 13 filters, based on the measurements of Stephens et al. [18] and modeling of Zaatari et al. [19] we assume an average 3% (2% to 4%) increase in HVAC energy use during cooling, no average change in fan energy during periods of fan-only operation, and no average change in heating energy. Based on the same sources, for intervention i8, which replaces MERV 8 filters in commercial building with MERV 11 filters we assume no significant changes in HVAC energy use. The basis for these assumptions is provided in the supporting information.

The costs of interventions i8 and i9, which increase the $PM_{2.5}$ removal efficiency of filters used in commercial buildings, is estimated at the national level because the required data were not available for each of the counties considered in this paper. As indicated above, we assume no significant incremental energy costs for i8 and an average 3% (2% to 4%) increase in HVAC energy use during space cooling for i9. In 2010, the U.S. stock of commercial buildings, with a floor area of 7.53×10^9 m^2, used an estimated 2.5×10^{11} kWh of electricity for space cooling and the average commercial building electricity price was \$0.1014 per kWh [20]. Thus, the estimated annual energy cost of implementing i9 in the entire U.S. stock of commercial buildings is \$$7.6 \times 10^8$ (\$$5.1 \times 10^8$ to \$$1.0 \times 10^9$). In this paper, benefits and costs are normalized by the number of residents of homes living in buildings that have a single home. Nationwide, in 2010 the U.S. had an estimated 87.6 million housing units in buildings containing only one

home and there were approximately 2.67 occupants per home [21]. Thus, the per-person annual energy cost of intervention i9 is $3.25 ($2.17 - $4.34). This is an overestimate because we have apportioned the cost entirely to residents of single-family homes. The estimated annual incremental cost per person of employing higher efficiency filters in i8 and i9 was estimated based on filter prices and replacement intervals, air velocities through filters, and a typical HVAC system supply air flow per unit floor area, with details provided in the supporting information. The resulting incremental annual cost per person was $1.60 for i8 and $5.72 for i9. For consistency with other estimates, these are costs per person in single family homes.

2.5 Sensitivity analysis

The measures of variance available for model inputs primarily indicate parameter variability among the samples of data, not uncertainty in central estimates. The modeling sampled among input parameter values to derive central estimates of model outputs. In a sensitivity analysis, the central values of model input parameters were varied. Values of the central estimates of the most influential and uncertain model inputs were decreased and increased by 25%, with no change in the assumed geometric standard deviations and standard deviations. The parameters varied by ±25% were: ventilation rates and air recirculation rates of homes and commercial buildings; duty cycle, clean air delivery rate (product of air flow and particle removal efficiency) of portable air cleaners; incremental costs of higher efficiency filters, and incremental $PM_{2.5}$ removal efficiency of higher efficiency filters. Additionally, the low and high estimates of the unit mortality risk coefficient for $PM_{2.5}$, based on the U.S. Environmental Protection Agency's low and high estimates [5], were employed in this analysis. Rather than assess the sensitivity of results to the variability of each individual parameter, we modeled all combination of permutations with the key parameters varied by ±25% and with the high and low estimates of the mortality risk coefficient. From this set of model runs, we determined the 2.5th and 97.5th percentile model outputs. The resulting ranges indicate the sensitivity of findings to the assumed variations in model inputs but do not reflect all sources of uncertainty.

3.0 MODEL INPUTS

Calculations are performed by season for the counties encompassing three U.S. cities [Los Angeles CA (Los Angeles County), Elizabeth NJ (Union County), and Houston TX (Harris County)] for which empirical data are available on home ventilation rates by season. Hereinafter, we use the city names to represent the counties. Ventilation rates for the three locations are based on measurements made with a perfluorocarbon tracer gas method in approximately 100 homes per location and reported by Yamamoto, Shendell [22]. The annual average ventilation rates for the three locations were 1.1 h^{-1}, 1.2 h^{-1}, and 0.67 h^{-1}, respectively, with substantial seasonal variability. Distributional data for ventilation rates are provided in Table S1 of the supporting information.

To calculate the duty cycle (fraction of time that the fan system operates) of home heating and air conditioning systems as a function on indoor-outdoor temperature difference and climate zone we use equations based on residential energy modeling for different climate zones [23]. Details are provided in the supporting information. The resulting values of duty cycle for winter,

spring, summer and fall are: 0.18, 0.11, 0.04, and 0.08 for Los Angeles; 0.54, 0.22, 0.09, 0.17 for Elizabeth; and 0.25, 0.1, 0.16, 0.13 for Houston TX.

We assume that the baseline homes have low-efficiency filters with an efficiency rating of MERV 6 based on a small study of the types of filters used in homes that found 55% of homes used a MERV 6 or lower-rated filter [24]. We assume that homes with filter efficiency upgrades employ a MERV 12 filter. However, because of air leakage (bypass) around higher efficiency filters when used in homes, the effective efficiency rating of the MERV 12 filters is assumed to be MERV 9 [15, 25]. We employ estimates of $PM_{2.5}$ removal efficiencies from Azimi et al. [26]. For the MERV 9 filter, we average the $PM_{2.5}$ removal efficiencies of the MERV 8 and MERV 10 filters. The resulting mean efficiency estimates are 7.5% for a MERV 6 filter and 29.8% for a MERV 9 filter, with distributional data in Table S3 of the supporting information.

Few data were identified on the efficiency ratings of filters used in in U.S. workplace buildings. Excluding data from prior to 2000, the identified data are compiled in the supporting information Table S4. Based on these data and the associated discussion in the supporting information, for commercial buildings, we assume that the typical filter has a MERV 8 rating. The interventions assume upgrades in efficiency to MERV 11 or MERV 13. Zaatari et al. [19] analyzed data for 60 filters and graphically provided their $PM_{2.5}$ removal efficiencies. The midpoint $PM_{2.5}$ removal efficiency values are 26%, 42%, and 66% for the MERV 8, 11, and 13 filters, respectively. Distributional data are in Table S5 of the supporting information.

For a central estimate of the mortality risk coefficient, β, for the all-age population, we use 1.06 per 1 $\mu g\ m^{-3}$ which was employed by the U.S. EPA in their evaluation of the Clean Air Act [5]. We also employ, as discussed below, the lower and higher values, 0.6 and 1.5 per 1 $\mu g\ m^{-3}$ cited in EPA's evaluation of the Clean Air Act. To calculate the change in premature mortality (Δy_i), we multiplied the fractional change in mortality by the baseline total mortality (y_o). Mortality rates, provided in Table 2 were determined from state health department data. Numbers of single family housing units and the average number of occupants per housing unit in Table 2 are based on U.S. Census data. Outdoor air $PM_{2.5}$ concentrations, also in Table 2, were determined for each location, separately for the winter, spring, summer, and fall periods based on data available from the U.S. EPA.

The estimated purchase prices of filters are based on data from Azimi and Stephens [17] and data available via the internet. For homes, we assume an average cost per filter of $4 for the MERV 6 filter and an average cost per filter of $9 for the MERV 12 filter. As a check, we averaged prices from three web sites marketing filters to the public, which led to $6.70 for a MERV 6 filter and $10.23 for the MERV 13 filter, resulting in a moderately lower incremental cost for high efficiency filters. For commercial buildings, we estimated an annual incremental filter purchase cost of $1.60 per person per year for use of MERV 11 versus MERV 8 filters and an annual incremental cost of $5.72 per person per year for use of MERV 13 versus MERV 8 filters, with details provided in the supporting information.

Table 2. Average baseline mortality rates, housing units, populations, and $PM_{2.5}$ concentrations for years 2010 - 2012.

Location	Age range	Annual total mortality per 10000 population	Occupied Single Family Housing Units[D]	Number of occupants per single family house[E]	Average House volume (m^3)	Average Outdoor Air $PM_{2.5}$ Concentrations[F] winter, spring, summer, fall $\mu g\ m^{-3}$
Elizabeth(Union County, NJ)[A]	All ages	72.5	103990	2.89	496	10.0, 9.1, 11.4, and 9.3
	Age ≥ 65	435	34320	1.35		
Los Angeles County, CA[B]	All ages	58.2	1815120	2.97	449	13.5, 10, 10.7, and 11.5
	Age ≥ 65	372	526400	1.33		
Houston (Harris County TX)[C]	All ages	55.8	853300	2.84	501	8.9, 10.2, 11.9, and 10.4
	Age ≥ 65	435	204800	1.38		

[A] Data from http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=DEC_10_DP_DPDP1&prodType=table and http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_14_5YR_B25001&prodType=table

[B] Data from https://dqs.publichealth.lacounty.gov/query.aspx?d=37 and http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk

[C] Data from http://soupfin.tdh.state.tx.us/cgi-bin/death10.htm and http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml

[D] one housing unit per building

[E] percentage from American Housing Survey http://www.census.gov/programs-surveys/ahs/data/2013/ahs-2013-public-use-file--puf-.html

[F,] https://www3.epa.gov/airdata/ad_data_daily.html

Table 3 lists additional model input parameters. Except as noted by footnotes, these parameter values are based on Fisk and Chan [15] which documents the sources of data.. Based on the consumer price index of the US Department of Labor, Bureau of Labor Statistics, prices obtained in 2016 were decreased by 5.8% to estimate prices in 2011.

Table 3. Values for additional parameters in mass balance and inhalation rate calculations.

Parameter	Value(s)[A]	Parameter	Value(s)	Parameter	Value(s)
λ_{VW} (h^{-1})	GM 1.06 GSD 2.56	$\varepsilon_P\ Q_P$ (h^{-1})	1.0	T_V (%)	5.5, 4.2 [C]
λ_{IW} (h^{-1})	0.1	K_V (-)	AM 0.6 SD 0.06	B_S ($m^3\ h^{-1}$)	0.58, 0.52 [C]
λ_{RW} (h^{-1})	AM 3.42 SD 2.79	V (m^3)	GM 404 GSD 1.47	B_{HA} ($m^3\ h^{-1}$)	0.71, 0.64 [C]
λ_D (h^{-1})	AM 0.39 SD 0.08	T_S (%)	37.0, 36.2[C]	B_W ($m^3\ h^{-1}$)	0.71, 0.64 [C]
λ_{DW} (h^{-1})	AM 0.39 SD 0.08	T_{HA} (%)	32.0, 44.6 [C]	B_O ($m^3\ h^{-1}$)	0.83, 0.81 [C]
P (-)	AM 0.97 SD 0.06[B]	T_W (%)	17.7, 8.3 [C]	B_V ($m^3\ h^{-1}$)	0.71, 0.64 [C]
Q (h^{-1})	GM 4.36 GSD 1.44	T_O (%)	7.5, 6.7 [C]	G_E ($/ kWh)	0.1180[D]
U_D Value of premature death ($)[G]	8.4×10^6	Z_{HAC} (W m^{-3} s^{-1})	1090	*E_P ($)[E]*	270 (Brand X) 687 (Brand Y)
Z_P (W m^{-3} s^{-1})[E]	920 (Brand X) 619 (Brand Y)	E_{RF} ($)[E]	197 (Brand X)[F] 228 (Brand Y) [F]		

[A]GM = geometric mean, GSD = geometric standard deviation, AM = arithmetic mean, SD = standard deviation

[B]cropped normal distribution with minimum of zero and maximum value of 1.0

[C]first value is for all ages, second value is for age ≥65

[D]US average residential electricity price in 2011, from Energy Information Administration, Table 8.10 https://www.eia.gov

[E]Unit air cleaner prices, filter replacement prices, and fan power in this table are scaled as needed for air cleaners that provide a clean air delivery rate for smoke of 520 $m^3\ h^{-1}$, equal to 1.2 indoor air volumes per hour in a house with a volume of 433 $m^{3'}$ for modeling these parameters are scaled by actual house volume

[F]the annual filter replacement costs are based on prices of filters and filter replacement intervals described in the text

[G]linear extrapolation between values for 1990 and 2020 from [27]

For interventions i1 – i7 which occur in homes, supplementary calculations were performed assuming that interventions occurred only in the subset of single family homes in which people with an age greater than or equal to 65 resided. Table 3 provides associated inputs for time spent in different environments and breathing rates. Table 2 provides the associated baseline mortality rates, numbers of houses and average numbers of persons per house with age greater than or equal to 65. For these calculations we used unit risk coefficients (values of β) for people in this age range provided by Zeger, Dominici [28]. The coefficient values (and 95% confidence intervals) are 0.0068 (0.0049 – 0.0087) for Elizabeth and 0.0132 (0.0096 0.0169) for Houston. For the western U.S., the study of Zeger et al. [28] did not find a statistically significant association of $PM_{2.5}$ with mortality, so no supplementary calculation was performed for Los Angeles. The reasons for the large variability among regions of the U.S. remain uncertain. One possible explanatory factor is the variability among the composition of particles. Relative to the unit risk estimates for the all-age population, these unit risks for the population with an age greater than or equal to 65 are based on much less research and are, therefore, less certain.

4.0 RESULTS

For base case homes, our model results indicated that 74% to 81% of the total inhalation of outdoor air $PM_{2.5}$ occurs when inside buildings, with a minimum of 60% of total $PM_{2.5}$ inhalation occurring indoors at home. These percentages suggest large opportunities to reduce $PM_{2.5}$-related health effects from interventions reducing particle concentrations indoors, particularly in homes.

Tables of results are provided in the supporting information. Figure S1 in the supporting information shows the effective annual average outdoor $PM_{2.5}$ concentrations (C_{OE}) for each intervention and location and, for reference, the actual annual average outdoor air $PM_{2.5}$ concentrations. In this figure and subsequent figures, when there are pairs of bars for an intervention the left bars depict the results of intervention 1a, 2a, 5a, and 6a with the duty cycle increased to 0.3 and the darker right bars depict the results of interventions 1b, 2b, 5b and 6b with the duty cycle increased to 0.4. Also, the error bars indicate the results of the sensitivity analysis, not the variability within the population. Intervention i1, which simply increases the operation time of the home HAC system fans, decreases C_{OE} by less than 5%. Intervention i3, which upgrades the home HAC filter but does not increase operation time, decreases C_{OE} by 4% to 9%. Intervention i2, which upgrades the HAC filter and increases operation time, is more effective, decreasing C_{OE} by 14% to 19%. Interventions i4 through i7 which incorporate continuously operating portable air cleaners, separately or in combination with home HAC measures, decrease C_{OE} by 26% to 36%. Intervention i8 which moderately increases the efficiency of filters in commercial building HVAC systems to MERV 11 decreases C_{OE} by less than 5% with the modest decrease substantially a consequence of the limited fraction of time spent in commercial buildings. Intervention i9, with a more aggressive upgrade in the HVAC filter in commercial buildings to MERV 13, decreases C_{OE} by 7% to 9%.

Figure 1 shows the predicted annual reductions in premature mortality per 10,000 population and the estimated associated annual monetary benefits per resident of single family homes for the Los Angeles location. The corresponding results for other cities are similar and are provided

in Figures S2 and S3 in the supporting information. The rather broad error bands are substantially a consequence of the uncertainty in the risk coefficient. The trends among interventions in these two parameters mirror the trends discussed above for reductions in C_{OE}. The reductions in annual premature mortality per 10,000 population equal 0.6 or less for interventions i1, i3, i8, and i9 (with one value of 0.67), equal about 1.0 for i2, and range from 1.8 to 2.4 for interventions i4 – i7. The annual economic benefits per person of these mortality reductions range from $110 for i1a (increases duty cycle to 30%) in Elizabeth to $2025 for i6b (increases duty cycle to 40%, high efficiency HAC filter, and portable air cleaner) in Elizabeth. For large populations, these modest sounding reductions in mortality per 10,000 population translate to sizable annual reductions in premature deaths. For example, interventions i4 – i6 are predicted to prevent more than 1000 premature deaths per year in Los Angeles County.

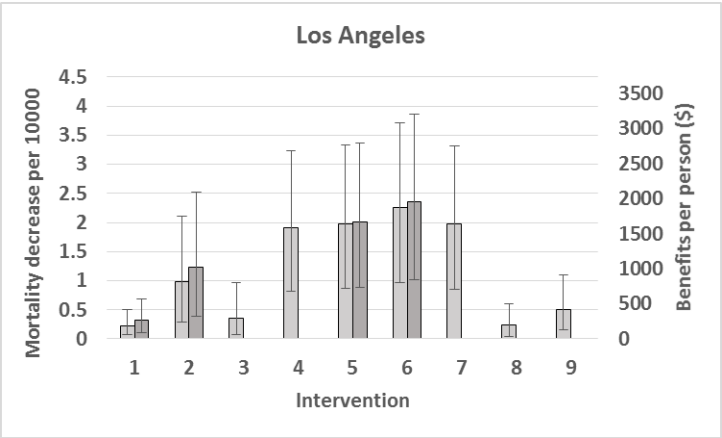

Figure 1. Mortality decrease and mortality-related economic benefits in Los Angeles.

Total annual intervention costs per person are depicted in Figure S4 in the supporting information. In figures involving costs, the results for the Brand Y air cleaner are not plotted, these results are similar to the results depicted for the Brand X air cleaner and are available in the tables in the supporting information. Total intervention costs per person are approximately $8 for i3 (upgrades the home HAC filter) and $25 to $75 for i1 and i2 which increases home HAC fan operation plus, for i2, also upgrades the HAC filter. The costs of i1b and i2b (right of pairs of bars), which force HAC fan operation time to at least 40% substantially exceed the costs of i1a and i2a (left of pairs of bars), which force HAC fan operation time to at least 30%. The total costs of the two models of portable air cleaners are similar. Compared to Model Y, Model X has a lower initial cost, higher energy cost, and similar annual filter replacement costs, with similar total costs. The annual per person costs of interventions i8 (upgrade to MERV 11) and i9 (upgrade to MERV 11) in commercial buildings are very low, approximately $2 and $6, respectively.

The benefit-cost (BC) ratios for Los Angeles are shown in Figure 2. The results for Elizabeth and Houston, in Figure S5 in the supporting information, are similar. All BC ratios are greater than unity and all lower limits of error estimates exceed unity. The BC ratios are lowest for intervention i1 (HAC duty cycle increases), equal to approximately 4.0 in all locations. Given the

low mortality benefits of i1, this is the least attractive intervention. Intervention i2, that increases home HAC filter efficiency and fan operation time, has BC ratios ranging from 14 to 25. The BC ratios from interventions that increase the home's minimum HAC fan operation time to 40% differ little from BC ratios from corresponding interventions that increase HAC minimum operation time to 30%. Also, the BC ratios are similar for the Brand X and Brand Y air cleaners. The BC ratios for interventions i4 – i7 which incorporate continuously operating portable air cleaners in homes range from approximately 6 to 13. Among these four interventions, the highest BC ratios occur for i4 which does not modify home HAC operation and for i7 which takes place in homes without central forced air HAC systems. The BC ratios for interventions i8 and i9, which increase the efficiency of filters in commercial buildings to MERV 11 and MERV 13, respectively, are very high ranging from approximately 74 to 133.

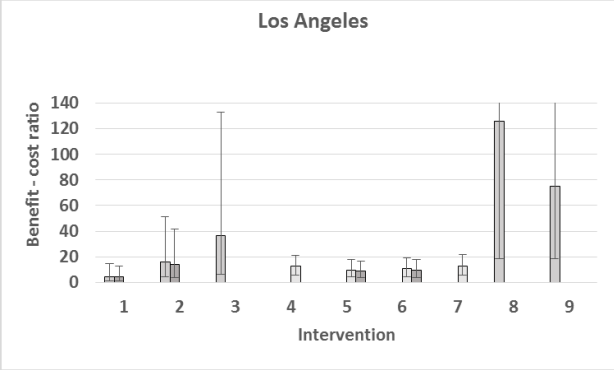

Figure 2. Benefit-cost ratios for interventions in Los Angeles. Some upper error bars extend above the scale. Values are available in the supporting information.

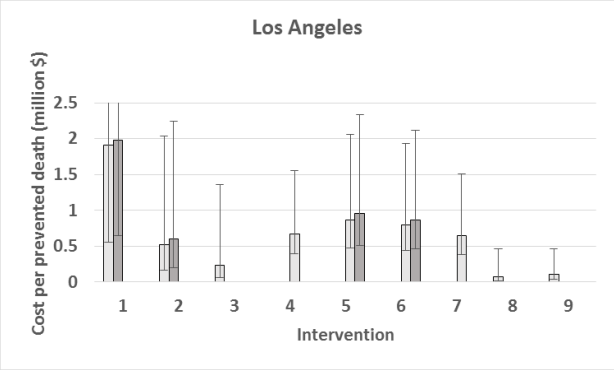

Figure 3. Costs per prevented premature death for interventions in Los Angeles. Some upper error bars extend above the scale. Values are available in the supporting information.

The costs for prevented premature death for Los Angeles are depicted in Figure 3, with corresponding results for other cities in Figure S6 in the supporting information. The interventions in commercial buildings, i8 and i9, have the lowest costs per prevented death, ranging from $ 0.06 million to $0.11 million. The highest costs per prevented premature death, about $2 million, occur for i1. The cost per prevented premature death of all other interventions range from $0.12 to $1.3 million. For reference, the cost of Clean Air Act measures per prevented particle-related death is $0.28 million [5]. Interventions i3, i8, and i9 have lower estimated costs per prevented premature death than the Clean Air Act.

Considering only the non-supplementary calculations, the model input parameters that varied among locations were: outdoor air $PM_{2.5}$ concentrations; home ventilation rates; duty cycles; house volumes, persons per house; and baseline mortality rates. Despite these differences, key results from the different locations, such as the mortality decreases per 10,000 population and benefit to cost ratios, are similar in magnitude. Also, the trends among the interventions remain the same, for example the highest reductions in mortality always occur for intervention

i6 which increases the efficiency of the HAC system filter, increases HAC operation time, and continuously operates a portable air cleaner.

The results of the supplementary calculations for interventions only in the homes with elderly residents indicate a large increase in intervention cost effectiveness. These elderly residents reside in one third of single family homes in Elizabeth and 24% of single family homes in Houston. Intervening only in this subset of homes reduces costs by a corresponding amount. The estimated prevented deaths decrease by about 30% when intervening only in homes with elderly residents in Elizabeth, and, on average, the BC ratio increases by a factor of two. For Houston, the estimated prevented deaths actually increase by approximately one third, relative to the estimated prevented deaths for interventions in all single-family houses, and on average the BC ratio increases by a factor of five. This projected increase in prevented deaths is a consequence of the high unit risk coefficient reported for $PM_{2.5}$ related mortality in the central region of the country [28].

5.0 DISCUSSION

This analysis indicates a potential to significantly reduce particle-related premature mortality via improvements in filtration in homes and commercial buildings. The largest mortality reductions identified, approximately 2 per year per 10,000 population, are projected from interventions in homes, particularly from interventions i4 – i7 which use continuously operating portable air cleaners. Substantial mortality reductions, approximately 1 per year per 10,000 population, are also predicted for intervention i2 which increases the efficiency of filters in home's HAC systems and also increases the operation time of the HAC fans. Only increasing HAC operation time (i1) or only increasing filter efficiency (i3) results in much smaller predicted reductions in mortality. Intervention i8 which modestly increases the efficiency of filters in commercial building HVAC systems from MERV 8 to MERV 11 is predicted to decrease premature mortality by approximately 0.25 per 10000 population, with about 0.5 per 10,000 population predicted for intervention i9 which increases filter efficiency from MERV 8 to MERV 13. The estimated BC ratios for the interventions always exceed unity. The highest BC ratios, ranging from about 74 to 133, are projected for low-cost interventions in commercial buildings. The BC ratios for intervention i3 are also particularly high, ranging from approximately 35 to 70. These high BC ratios are a consequence of very low intervention costs, not a result of large reductions in premature mortality. Interventions i4 – i7, with continuously operating portable air cleaners are projected to have much higher mortality benefits with BC ratios ranging from approximately 6 to 13.

The supplementary analysis indicates a large increase in cost effectiveness from intervening only in the subset of homes with an elderly population. However, our predictions for the elderly population have increased uncertainty because the associated unit risks for $PM_{2.5}$-related mortality for the elderly population are not as well substantiated as the unit risks for the all-age population.

Our higher predicted mortality reductions from scenarios with portable air cleaners are a consequence of higher particle removal rates of portable air cleaners in our scenarios and not a

consequence of an inherent advantage of portable air cleaners. Relative to improvements in filtration of home HAC systems, portable air cleaners have both advantages and disadvantages. Portable air cleaners are simply added, can be located where people spend their time, can be relocated, and can be used in homes without central forced air HAC systems. Improvements in filtration by home HAC systems may require changes in HAC system hardware and controls. In an ongoing study, we have found it prohibitively expensive in many older homes to upgrade HAC controls so that fans can operate when heating and cooling is not necessary. Portable air cleaners will also often use less energy, per unit particle removal, than upgrades to HAC system filtration [29]. However, upgrades to filtration of central forced air HAC systems will provide more spatially uniform reductions in particle concentrations than portable air cleaners. A poor selection of location for a portable air cleaner could very substantially reduce the extent to which the air cleaner diminishes particle exposures [30].

The economic benefits of reduced premature mortality were calculated based upon a unit value for premature death employed by the US Environmental Protection Agency in their analysis of the Clean Air Act. Estimates of the economic value of a prevented premature death vary substantially. A review for the US Environmental Protection Agency found that "most of the reasonable estimates of the value of life…" are within ± 40% of the central estimate [27]. Our estimated economic benefits of improved filtration scale directly with the unit value of a premature death. However, even with a 40% reduction in the unit value for premature mortality, all benefit-cost ratios would remain well above unity.

Relative to prior related papers, this analysis has several strengths. A wide range of interventions are assessed, including interventions in both homes and commercial buildings. Both costs and mortality reductions are evaluated. The analysis uses the latest available information on the energy implications of filtration. The analysis is the first to explicitly account for time spent, and activity levels and breathing rates, in different environments and the first to account for seasonal variability in home ventilation rates. Variability among homes and commercial buildings is captured by sampling from distributions of model input parameters. In addition, we modeled the potential sensitivity to changes in key input parameters. Finally, the calculation of effective outdoor air $PM_{2.5}$ concentrations results in an intuitive metric of intervention effectiveness.

Our analysis also has several limitations. The only health benefit assessed is a reduction in mortality. Morbidity reductions were not considered. Also, the health benefits of reducing indoor concentrations of indoor-generated particles, which may be considerable, are not considered. We have estimated the numbers of prevented premature deaths which is a common practice; however, this metric does account for the amount by which life is shortened. For multiple reasons, estimation of the reduction in life expectancy may be preferable [31]. The seasonal calculations, performed with steady state models, do not capture the effects of diurnal or day to day variability in home ventilation rates, outdoor particle concentrations, and operation of HAC systems for heating and cooling. We cannot rule out the possibility of an associated bias in the predicted mortality reductions, but suspect that any bias would be small. Because the relationship of $PM_{2.5}$ exposures with mortality is close to linear, our need is to

estimate the time average reductions in $PM_{2.5}$ concentrations as a result of filtration system improvements. The use of a model for well mixed indoor air is a simplification, requiring a discounting of the clean air delivery rate of the portable air cleaners. Some instances of imperfect mixing will decrease the filtration benefits, while in other instances imperfect mixing will increase filtration benefits [15]. For the sensitivity analysis, the assumed magnitude in variability of central values of key model inputs was based on judgment because uncertainty data are largely unavailable.

Comparisons with prior related analyses can only be qualitative because of the differences among scenarios assessed. The previous analyses summarized in our Introduction section, have predicted substantial reductions in morbidity and mortality, consistent with our prediction in substantial decreases in premature mortality. The prior studies with benefit cost analyses [9, 11] have projected that health-related economic benefits far exceed filtration costs, consistent with our findings.

The high BC ratios for the filtration interventions suggest, at a minimum, that there be routine use of higher efficiency filters in home HAC systems and commercial building HVAC systems and upgrades to the associated minimum filtration efficiency requirements in standards. For example, the commercial building ventilation standard of the American Society of Heating, Refrigerating, and Air Conditioning Engineers [32] has a minimum filter efficiency of MERV 8, with MERV 11 required only where outdoor air particle levels are high. Based on our findings and those of [9], the minimum required filter efficiency should be increased, e.g., to MERV 11 or higher. Our findings also suggest that concerned home owners who are able to accommodate the costs may want to continuously operate portable air cleaners with high efficiency filters in their homes, particularly if occupants are elderly or have respiratory or cardiac health conditions that increase their susceptibility to particle-related health effects. In selection of portable air cleaners, costs over time, including energy and filter replacement costs, should be considered as these ongoing costs can exceed the initial purchase price.

An extrapolation of our results to the full U.S. population leads to a very large national-level potential mortality reductions and mortality-related economic benefits. The largest benefits are from interventions that use portable air cleaners, these could be employed in nearly all homes and apartments. They result in predicted mortality reduction of approximately 2 per 10,000 population. For the total U.S. population of approximately 320 million, this mortality reduction rate corresponds to 64,000 prevented premature deaths each year. For several of the interventions, the estimated mortality related economic benefits exceed $1000 per person per year, with peak estimates exceeding $2000 per person per year. For the full U.S. population, a $1000 per year per person benefit translates to a potential nationwide annual benefit of $0.32 trillion. This extraordinary potential benefit, together with the predicted high benefit-cost ratios, suggest that much greater attention be placed on improvements in particle filtration.

6.0 CONCLUSIONS

Based on our analysis:

1. Particle-related premature mortality can be significantly decreased via improvements in filtration systems in homes and commercial buildings.
2. Increasing both the efficiency of filters in home HAC systems and the operation time of HAC fans is much more beneficial than increasing either one of these factors alone.
3. The economic benefits of the filtration interventions always exceeded costs, in most cases by more than a factor of ten.
4. The cost per prevented premature death of three of the interventions is less than the estimated cost per prevented particle-related death of the pollution control measures in the Clean Air Act.

7.0 ACKNOWLEDGMENTS

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Effectiveness and Cost of Reducing Particle-Related Mortality with Particle Filtration

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SUPPORTING INFORMATION

Nomenclature

Symbol	Parameter
B_{HA}	Inhalation air intake rate when home and awake
B_O	Inhalation rate when outdoors
B_S	Inhalation rate when home and sleeping
B_V	Inhalation rate when in a vehicle
B_W	Inhalation rate when indoors away from home
C_{B1}	PM2.5 concentration at home for baseline condition B1
C_{B2}	PM2.5 concentration at home for baseline condition B2
C_N	PM2.5 concentration at home for intervention N
C_O	PM2.5 concentration outdoors
C_{OE}	Equivalent outdoor air PM2.5 concentration
CST_{AC}	Annual cost per house of portable air cleaner and its operation
CST_P	Incremental cost per person of purchasing higher efficiency filters
C_V	PM2.5 concentration in vehicles
C_W	PM2.5 concentration when indoors away from home
D	Duty cycle, i.e., fraction of time the fan of the forced air heating and cooling system operates. D_N refers to the duty cycle for intervention N
D_{HC}	Duty cycle of home heating and cooling system needed for space heating and cooling
E_H	Incremental cost of high efficiency filter
E_{HAC}	Incremental heating and air conditioning system electricity cost per home
E_P	Cost of portable air cleaner
E_{RF}	Annual cost of replacement filters for portable air cleaner
F_N	Economic value of prevented deaths for intervention N
G_E	Electricity price
I_{B1}	Total PM2.5 intake for baseline condition B1
I_{B2}	Total PM2.5 intake for baseline condition B2
I_N	Total PM2.5 intake for intervention condition N
K_{B1}, K_{B2}	Constants relating PM2.5 concentrations in home to outdoor air PM2.5 concentration, for baseline conditions B1 and B2
K_N	Constant relating PM2.5 concentrations in home to outdoor air PM2.5 concentration, for intervention condition N
K_V	Constant relating PM2.5 concentrations in vehicle to outdoor air PM2.5 concentration

K_W	Constant relating PM2.5 concentrations indoors away from home to outdoor air PM2.5 concentration
N	Time of air cleaner operation per year
N_H	Number of homes
O_H	Average number of occupants per home
P	Particle penetration factor, i.e., the fraction of particles that penetrate through the building envelope during air infiltration
Q	Air flow rate in the home's forced air heating and cooling system divided by the indoor volume
PD	Prevented deaths
P_H	Price of higher efficiency filter
P_L	Price of lower efficiency filter
Q_P	Air flow rate in the portable air cleaner divided by the indoor volume
T	Elapsed time in hours
T_O, T_S, T_{HA}, T_W , T_V	Time spent outdoors (subscript O), home asleep (subscript S), home awake (subscript HA) indoors away from home (subscript W), in vehicles (subscript V)
U_D	Economic value of an avoided death
V	House volume
y_o	Baseline total mortality rate
Z_{HAC}	Power consumption of the forced air heating and cooling system fan per unit air flow
Z_P	Power consumption of the portable air cleaner fan per unit air flow
β	Risk coefficient for PM2.5 caused mortality
ε_H	PM2.5 removal efficiency of the higher efficiency filter in the home's forced air system during interventions i2, i3, and i6
ε_L	PM2.5 removal efficiency of the low efficiency filter normally used in the forced air heating and cooling system of the home
ε_p	PM2.5 removal efficiency of the portable air cleaner
ε_W	PM2.5 removal efficiency of the particle filter used for buildings other than the home
ΔI	Reduction in PM2.5 inhalation intake attributable to intervention
λ_D	Rate of particle removal by deposition on indoor surfaces, normalized by indoor volume
λ_{DW}	Rate of particle removal by deposition on indoor surfaces in buildings other than the home, normalized by indoor volume
λ_F	Rate of particle removal by the home's forced air heating and air conditioning system in the absence of an intervention, normalized by indoor volume
λ_{IW}	Air infiltration rate in buildings other than the home, normalized by indoor volume
λ_{MW}	Flow rate of outdoor air supplied mechanically in buildings other than the home, normalized by indoor volume
λ_N	Rate of particle removal by filtration in the home during intervention N, normalized by indoor volume
λ_{RW}	Mechanical recirculation air flow rate in buildings other than the home, normalized by indoor volume
λ_V	Infiltration ventilation rate of the home, normalized by indoor volume
λ_{VW}	Total ventilation rate in buildings other than homes
$\Delta y_i / y_o$	Fractional change in total mortality
$\Delta PM2.5$	Change in outdoor air PM2.5 concentration in micrograms per cubic meter corresponding to the change in total PM2.5 inhalation intake due to the filtration intervention

Effective clean air delivery rate of portable air cleaners

Portable air cleaners preferentially clean air near their location, reducing the total rate of particle removal relative to the idealized well mixed assumption. The indoor air is often not fully mixed; however, the imperfect mixing from portable air cleaning can affect indoor particle exposures positively or negatively. If people tend to place portable air cleaners near to locations where they spend an above average amount of time, their particle exposures may be decreased more than with perfect mixing. If people tend to place air cleaners away from where they spend time, their particle exposures may be decreased by less than with perfect mixing. Given that we lack systematic data on the locations of portable air cleaners in homes, the average impact of imperfect mixing on the exposure reductions of portable air cleaners remains uncertain. Novoselac and Siegel (2009) explored this issue with computational fluid dynamics modeling for a specific house geometry, with a specific set of boundary conditions, in a home without operation of a central forced air system. With a centrally located portable air cleaner having a flow of two indoor air volumes per hour, they predicted that indoor volume-average particle concentrations, for 0.74 µm particles were decreased by 85% of the decrease expected with perfect mixing. For 3.2 µm particles, the corresponding number was 88%. However, with one air cleaner location, these percentages dropped to below 50%. These percentages would correspond to effects of enhanced local air cleaning on exposures for an occupant that used all indoor spaces in proportion to their volume. For a few reasons, imperfect mixing is likely to have a smaller effect in our scenarios. Our air cleaner has a smaller airflow rate per unit volume, increasing the ratio of natural indoor air mixing to particle removal by the portable air cleaner, diminishing the enhanced local depression of particle concentrations near the air cleaner. Second, the results of Novoselac and Siegel (2009) are for a home with a localized strong indoor particle source, while our modeling considers only particles from outdoor air. Third, our base case 1 homes have central forced air heating and cooling systems which facilitate mixing. To account for the effects of enhanced localized air cleaning of portable air cleaners, we assume that the rated clean air delivery rate of the portable air cleaner must be 120% of the house volume per hour to achieve the particle removal equivalent to a clean air delivery rate of one indoor air volume per hour in a well-mixed space. This 120% value is approximately the reciprocal of 85%, found by Novoselac and Siegel (2009) for 0.74 µm particles with a centrally located portable air cleaner.

Frequency of replacing filters in portable air cleaners

There is evidence that the air flow rates of at least some portable air cleaners will decrease over time as the filters load with collected particles. These reductions in airflow rates diminish the rate of particle removal of the air cleaners. For a HEPA-based portable air cleaner, Zuraimi et. al. (2016) reported a reduction in clean air delivery rate from 600 to 390 m3/h (a 35% reduction) after loading the filter with an ultrafine test dust with a deposited dust mass equivalent to filtering air with 30 µg m^{-3} of particles for six months. This dust loading rate, based on an assumed indoor particle concentration of 30 µg m^{-3}, may be higher than typical in U.S. homes, particularly homes with operating air cleaners. Also, the fine test dust may have a larger impact on airflow than typical indoor air particles containing many larger particles. Shaughnessy et. al. (1994) reported a 26% decrease in flow rate of a HEPA based portable air cleaner after six months of continuous operation in a home. The effects of dust loading on air flow rates and clean air delivery rates will vary among portable air cleaners. Some newer portable air cleaners have electronically commutated motors and controls which presumably maintain flow as the filter loads. Also, replacing or cleaning prefilters, assumed in our scenarios, is likely to diminish flow rate decreases and neither Zuraimi et. al. (2016) or Shaughnessy et. al. (1994) mention any cleaning or replacement of prefilters. Nevertheless, a significant reduction in airflow seems likely for some air cleaners if filters are

replaced at the frequency recommended by the manufacturers. Consequently we have doubled the manufacturer's recommended replacement frequency for HEPA filter of the Brand X air cleaner and doubled the manufacturer's recommended replacement frequency of filters of the Brand Y air cleaner.

Effects of increases in particle filter efficiency on HVAC energy consumption

The influence of filter efficiency upgrades on HVAC energy use in commercial buildings is expected to be small and variable, depending on the HVAC system characteristics and operation times. When higher efficiency filters have an increased airflow resistance, fan power may decrease or increase, fan operation times may change, and the thermodynamic efficiency of cooling systems may decrease. Stephens et. al. (2010) investigated the effects of filter efficiency on airflow resistance of filters and HVAC energy use in nine homes and eight small commercial buildings. They compared filters with very low (MERV 2), medium (MERV 6-8) and high (MERV 11-12) efficiency ratings. There was no significant difference between the airflow resistance of the medium and high efficiency filters. The use of more highly pleated or deeper filters as the efficiency rating increases could explain how efficiency ratings can increase without an increase in airflow resistance. In this study, the use of high efficiency versus medium efficiency filters also did not significantly affect heating, ventilating, and air conditioning (HVAC) system energy use. The use of high efficiency versus low efficiency filters had a very small beneficial effect on HVAC energy use.

Zaatari et. al. (2014) employed a combination of measurements and modeling to assess the impacts of changing from MERV 8 to MERV 11, MERV 13, or MERV 14 filters in commercial buildings with HVAC systems without and with fan speed control. Higher efficiency filters, when they have a higher airflow resistance, reduce fan power but also decrease the HVAC system energy efficiency ratio (EER) in HVAC systems without fan speed controls. Also, if the fan is operated intermittently, its operation time (duty cycle) will also increase during periods of space cooling. During time periods of fan operation without active cooling (fan-only operation), fan energy use decreases and EER is not a factor. Higher efficiency filters, when they have an increased airflow resistance, increase fan power in HVAC systems with fan speed controls. EER and duty cycle are not affected. The authors did not discuss the effects on heating energy use. Increases or decreases in energy used by fans will lead to corresponding decreases or increases in the energy that must be supplied by the heating system, although, when the heat is provided by gas, it will normally have a lower cost that the electricity used by fans. The analysis by Zaatari et. al. (2014) indicated that use of MERV 11 filters in place of MERV 8 filters has a minimal impact on energy consumption. We will assume no significant changes in energy use for intervention i8 in which MERV 8 filters are replaced by MERV 11 filters. The analysis by Zaatari et. al. (2014) indicated that use of MERV 13 or MERV 14 filters in place of MERV 8 filters increased HVAC energy use during cooling by 2% to 4% with and without fan speed control. During periods of fan-only operation, use of the higher efficiency filters decreased fan energy by 8% to 13% in HVAC systems without fan speed controls and increased fan energy by 11% to 18% in HVAC systems with fan-speed controls. Approximately one third of the commercial building floor space in the U.S. is served by HVAC systems with fan speed controls (Hao et. al. , 2014). Thus, overall for U.S. commercial building stock there would probably be a small energy savings during periods of fan-only operation when higher efficiency (MERV 13 or MERV 14) filters are employed. Intervention i9 in our analysis uses MERV 13 filters in place of MERV 8 filters within workplaces and other commercial buildings. The effects of this intervention on HVAC energy use will be small but will vary among buildings and climates. Based on the prior discussion, we will assume an

average 3% (2% to 4%) increase in HVAC energy use during cooling, no average change in fan energy during periods of fan-only operation, and no average change in heating energy; however, we acknowledge the high uncertainty in these estimates.

Residential ventilation rates.

Ventilation rates for the three locations are based on measurements reported by Yamamoto et. al. (2010) in approximately 100 homes per location. The measurements were made with a perfluorocarbon tracer gas method and the measured rates are reported for each season. The resulting ventilation rates are provide in Table S1

Table S1. Residential ventilation rates

City	Season	10th %ile*	25th %ile*	Median	Mean	75th %ile*	90th %ile*	Geometric mean^	Geometric standard deviation^
Los Angeles	winter	0.25	0.38	0.61	0.75	0.90	1.38	0.59	1.94
Los Angeles	spring	0.56	0.74	0.87	1.17	1.53	2.24	1.04	1.72
Los Angeles	summer	0.38	0.71	1.13	1.52	1.86	2.96	1.11	2.19
Los Angeles	fall	0.34	0.45	0.80	0.99	1.24	1.84	0.77	1.97
Elizabeth	winter	0.44	0.61	1.07	1.41	1.84	2.87	1.09	2.12
Elizabeth	spring	0.44	0.53	0.63	1.13	1.36	1.95	0.83	1.83
Elizabeth	summer	0.31	0.64	0.88	1.27	1.68	2.92	0.97	2.32
Elizabeth	fall	0.35	0.57	0.81	1.05	1.26	2.10	0.84	1.96
Houston	winter	0.24	0.39	0.63	0.74	1.00	1.35	0.60	1.97
Houston	spring	0.26	0.31	0.38	0.73	0.56	2.10	0.51	2.08
Houston	summer	0.16	0.23	0.37	0.52	0.54	1.12	0.38	2.08
Houston	fall	0.18	0.33	0.48	0.69	0.73	1.31	0.49	2.08

*not available in paper but provided by authors ^estimated from percentile data

Residential duty cycle predictions

We use equations for the duty cycle (fractional run time) of home heating and air conditioning systems as a function on indoor-outdoor temperature difference and climate zone that were developed by (Logue et. al. , 2012) based on residential energy modeling for different climate zones. Table S2 provides parameters *m* and *b* for equations of the form

$$D = m\,x + b$$

where D is the duty cycle and *X* is the difference between the thermostat setting temperature and the outdoor temperature in degrees Celsius. In this table, values of m and b are provided for new, average, and old homes. The equations are only valid when D is between zero and unity and the predictions of duty cycle during heating are only valid when the outdoor temperature is below the heating thermostat set point. Similarly, the predictions of duty cycle during cooling is only valid when the outdoor temperature exceeds the cooling thermostat set point. The modeled new homes were most energy efficient and air tight while the modeled old homes were least energy efficient and air tight. We employ the coefficients for the average home. For three locations, Elizabeth NJ, Los Angeles, and Houston, the climate zones are 4A, 3C, and 2A, respectively. For Los Angeles, we use the duty cycle parameters for

climate zone 3C (where C refers to a marine climate). Los Angeles is at the boundary of climate zones 3B and 3C. Thermostat setpoints were based on the recommendations of (Logue et. al., 2012).

Table S2. Parameters for duty cycle calculations.

IECC Climate Zone	Average House			
	slope (m)		intercept (b)	
	Heating	Cooling	Heating	Cooling
4A (Elizabeth NJ)	0.03	-0.05	-0.08	0.10
3C (Los Angeles, CA)	0.04	-0.04	-0.12	0.19
2A (Houston TX)	0.04	-0.04	-0.08	0.10

The duty cycle calculation referenced above is applicable to homes in which the HVAC system's fan only operates to the extent needed to provide space heating and cooling.

PM2.5 removal efficiencies of filters used in home heating and cooling systems

The PM2.5 removal efficiencies of filters used in forced air systems are based on analyses by Azimi et. al. (2014). They used data on the size distributions of outdoor air PM2.5 together with a model of depositional particle losses by particle size in homes to predict indoor PM2.5 size distributions. These indoor PM2.5 size distributions were combined with data from Hecker and Hofacre (2008) on the particle removal efficiency versus particle size of commercially available filters to estimate the PM2.5 removal efficiencies of filters with various MERV efficiency ratings.

Table S3. PM2.5 removal efficiency of residential filters.

MERV	5th %ile	25th %ile	50th %ile	75th %ile	95th %ile	Distribut-ion	Mean	Standard Deviation
6	5.5	6.1	6.7	7.7	10.4	Normal	7.5	1.3
8	21.5	24.0	26.0	28.8	35.5	Normal	27.8	3.9
10	26.4	28.2	30.0	32.6	39.4	Normal	31.9	3.7

PM2.5 removal efficiencies of filters used in commercial HVAC systems

Table S4 compiles the identified data of the efficiency ratings of filters in commercial buildings located in the U.S.

Table S4. Filters used in commercial buildings located in the U.S.

Study	Buildings	PM2.5 Efficiency Ratings
(Bennett et. al. , 2012)	32 small and medium-size commercial buildings in California	62% MERV ≤ 4 filters 35% MERV 6 to 8 filters 3% MERV 12 filters
(Chan et. al. , 2012)	15 retail buildings in California	5 MERV 2 filters 9 MERV 8 filters 1 MERV 15 filter
(Mendell et. al. , 2015)	16 office buildings in California	14 MERV 8 filters 2 MERV 14 filters
(Zaatari and Siegel, 2014)	14 retail stores in Texas and Pennsylvania	All stores had MERV 6 to 8 filters

Based on this compilation, most U.S. commercial buildings employ filters with a MERV 8 or lower rating. Until recently, the minimum ventilation standard of the American Society of Heating, Refrigerating, and Air Conditioning Engineers required a MERV 6 or better filter, except where particle concentrations do not meet standards where MERV 11 filters were required. In a recent change, the minimum efficiency rating of filters upstream of a coil was changed to MERV 8. However, this is a building design standard, and actual practice may differ. We assume that the typical baseline filter has a MERV 8 rating. The interventions assume upgrades in efficiency to MERV 11 or MERV 13.

Zaatari et. al. (2014) analyzed data for 60 filters and graphically provided their PM2.5 removal efficiencies. Table S5 provides their minimum, maximum, and the midpoint PM2.5 removal efficiency for filters with MERV 8, 11, and 13 efficiency ratings. We assumed a triangular distribution with min, mid-point, max efficiency as specified in the table.

Table S5. PM2.5 removal efficiencies of filters from (Zaatari et. al., 2014).

MERV rating	Minimum Efficiency %	Mid-point Efficiency %	Maximum Efficiency %
8	9	26	43
11	22	42	62
13	53	66	80

The efficiency ratings of commercial HVAC filters were not discounted to account for air leakage (bypass) around filters. In measurements with a typical commercial building filter bank, with undamaged filter frames and undamaged filters, bypass rates were only 1% to 3% of the rate of flow through the filters (Fisk et. al. , 2003). However, we acknowledge that the current limited knowledge about bypass rates in commercial building filter systems.

Prices of commercial building HVAC filters

Table S6, provides estimates of a typical purchase price of filters with a 0.6 m by 0.6 m face area based on Azimi and Stephens (2013).

Table S6. Estimated typical filter price versus MERV rating for a 0.6 m by 0.6 m filter based on data from Azimi and Stephens (2013).

MERV rating	Price ($US)
4	2*
7	4*
8	4.3#
11	7*
13	11*

*from (Azimi and Stephens, 2013) #Calculated from curve fit to data from (Azimi and Stephens, 2013)

We conducted a search of the prices of filters available for purchase via the internet and this search indicated generally higher prices than reported by Azimi and Stephens (2013) for filters with the same size and MERV rating. We considered only basic filters, excluding for example filters with a high media area intended to be used a full year and filters incorporating media for removing gas phase pollutants. We found that basic MERV 8 filters cost approximately $8, MERV 11 filters costs approximately $13 ($11 to $15) and MERV 13 filters cost approximately $19 ($15 to $23). To be conservative, i.e., not underestimate the incremental cost of higher efficiency filtration, we estimated incremental filter prices based on Table S7 and we assumed use of four filters per year at higher MERV ratings. Using available data, the cost per person per year were estimated. For consistency with other cost estimates, these are costs per person residing in homes located in buildings with only one home.

Table S7. Estimated typical filter price versus MERV rating, with filter prices from a search of products available via web sites, plus calculation of cost per person.

MERV rating	Price ($US)	Face Area (m^2)	Face velocity (m/s)	Replacement interval (months)	Supply Air Flow (m^3 s^{-1} per m^2 floor area)*	Cost ($ per m^2 per year)	Cost ($ per person per year^)
8	8	0.36	2	3	0.00512	0.228	7.33
11	13	0.36	2	4	0.00512	0.277	8.93
13	19	0.36	2	4	0.00512	0.405	13.05
11 - 8							1.60
13 - 8							5.72

*From (Persily and Gorfain, 2008) ^Calculation relies on the 2.50×10^{11} floor area of the US commercial building stock (Department of Energy, 2010) and the 2.34×10^{8} residents in U.S. homes within buildings with only one home (U.S. Census Bureau, 2016).

Results

Table S8. Results for Los Angeles.

Los Angeles	i1a	I1b	i2a	i2b	i3	i4	i5a	I5b	i6a	I6b	i7	i8	i9
Effective outdoor PM2.5 (μg m^{-3})	11.1 (10.9 - 11.2)	10.9 (10.6 – 11.1)	9.8 (9.0 - 10.6)	9.4 (8.5 – 10.3)	10.9 (10.3 – 11.2)	8.3 (7.6 - 9)	8.2 (7.5 - 8.9)	8.1 (7.5 - 8.8)	7.7 (7.0 - 8.5)	7.6 (6.8 - 8.4)	8.2 (7.5 - 8.9)	11 (10.7 - 11.3)	10.6 (10.2 - 11.0)
Fractional mortality reduction	*0.0039 (0.0013 - 0.0087)*	*0.0057 (0.002 – 0.0119)*	*0.017 (0.005 - 0.0362)*	*0.0211 (0.0067 - 0.0433)*	*0.006 (0.0013 - 0.0165)*	*0.0328 (0.0141 - 0.0557)*	*0.0341 (0.0148 - 0.0572)*	*0.0346 (0.0151 - 0.058)*	*0.0387 (0.0167 - 0.0639)*	*0.0403 (0.0174 - 0.0664)*	*0.0339 (0.0146 - 0.0571)*	*0.0041 (0.0008 - 0.0103)*	*0.0088 (0.0028 - 0.0189)*
Mortality decrease per 10,000	0.23 (0.07 – 0.50)	0.33 (0.11 - 0.69)	0.99 (0.29 = 2.11)	1.23 (0.39 - 2.52)	0.35 (0.07 – 0.96)	1.91 (0.82 – 3.24)	1.98 (0.86 - 3.33)	2.01 (0.88 - 3.37)	2.25 (0.97 - 3.72)	2.35 (1.01 - 3.86)	1.97 (0.85 - 3.32)	0.24 (0.04 - 0.60)	0.51 (0.16 - 1.1)
Prevented deaths	123 (40 - 272)	179 (62 - 374)	534 (158 - 1137)	661 (210 - 1358)	189 (40 - 518)	1030 (441 - 1747)	1069 (464 - 1796)	1085 (475 - 1818)	1213 (523 - 2004)	1264 (547 - 2083)	1062 (457 - 1792)	129 (24 - 323)	275 (87 - 592)
Benefits per person ($)	191 (62 - 423)	279 (96 – 583)	832 (246 - 1771)	1031 (328 - 2116)	294 (62 - 807)	1605 (687 - 2723)	1666 (723 - 2799)	1691 (740 - 2833)	1890 (815 - 3122)	1970 (852 - 3246)	1656 (712 - 2792)	202 (37 - 503)	428 (136 - 923)
Energy cost per person ($)	44 (28 - 50)	66 (45 - 77)	44 (28 - 50)	66 (45 - 77)	0	NA	NA	NA	NA	NA	NA	0	3.3 (2.2 - 4.3)
Brand x air cleaner	NA	NA	NA	NA	NA	40 (-)	84 (68 - 90)	106 (85 - 117)	84 (68 - 90)	106 (85 - 117)	40 (-)	NA	NA
Brand y air cleaner	NA	NA	NA	NA	NA	27 (-)	70 (55 - 77)	93 (72 - 104)	70 (545- 77)	93 (72 - 104)	27 (-)	NA	NA
Total cost per person ($)	44 (28-50)	66 (45 - 77)	52 (35 - 60)	74 (51 - 87)	8 (6 - 10)	NA	NA	NA	NA	NA	NA	1.6 (1.2 - 2.0)	5.7 (4.0 - 7.4)
Brand X air cleaner	NA	NA	NA	NA	NA	128 (-)	171 (156 - 177)	193 (173 - 205)	179 (162 - 188)	202 (179 - 215)	128 (-)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	155 (-)	198 (183 - 204)	220 (200 - 232)	206 (189 - 214)	228 (206 - 242)	155 (-)	NA	NA
Benefit cost ratio	4.4 (1.3 - 14.9)	4.3 (1.2 - 13)	16.1 (4.1 - 51.3)	14.0 (3.8 – 41.4)	36.4 (6.2 – 133.2)	NA	NA	NA	NA	NA	NA	126.1 (18.4 – 419.5)	74.9 (18.3 – 229.3)
Brand X air cleaner	NA	NA	NA	NA	NA	12.6 (5.4 - 21.3)	9.7 (4.1 - 17.9)	8.7 (3.6 - 16.4)	10.5 (4.3 – 19.2)	9.8 (4.0 - 18.1)	13 (5.6 — 21.8)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	10.4 (4.4 — 17.6)	8.4 (3.5 - 15.3)	7.7 (3.2 - 14.2)	9.2 (3.8 - 16.5)	8.6 (3.5 — 15.8)	10.7(4.6 — 18.1)	NA	NA
Cost per prevented death $M	1.91 (0.6 - 6.7)	1.98 (0.65 - 6.74)	0.52 (0.16 - 2.04)	0.60 (0.20 - 2.24)	0.23 (0.06 – 1.36)	NA	NA	NA	NA	NA	NA	0.07 (0.02 - 0.46)	0.11 (0.04 - 0.46)
Brand X air cleaner	NA	NA	NA	NA	NA	0.67 (0.39 - 1.56)	0.86 (0.47 - 2.06)	0.96 (0.51 - 2.33)	0.80 (0.44 - 1.93)	0.86 (0.46 – 2.12)	0.65 (0.38 - 1.51)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	0.81 (0.48 - 1.89)	1.0 (0.55 – 2.37)	1.09 (0.59 – 2.2.63)	0.92 (0.51 - 2.21)	0.97 (0.53 — 2.39)	0.78 (0.47 - 1.82)	NA	NA

Table S9. Results for Elizabeth.

Elizabeth	i1a	I1b	i2a	i2b	i3	i4	i5a	I5b	i6a	I6b	i7	i8	i9
Effective outdoor PM2.5 (μg m^{-3})	9.8 (9.6 – 9.9)	9.7 (9.5 – 9.8)	8.6 (7.9 – 9.2)	8.3 (7.6 - 9)	9.1 (8.4 – 9.6)	7.4 (6.8 – 8.0)	7.3 (6.7 – 7.9)	7.3 (6.7 – 7.9)	6.9 (6.3 – 7.6)	6.8 (6.2 – 7.5)	7.2 (6.6 – 7.8)	9.6 (9.4 – 9.8)	9.2 (8.8 – 9.5)
Fractional mortality reduction	0.0018 (0.0005 – 0.0046)	0.003 (0.001 – 0.0067)	0.0142 0.0042(- 0.0303)	0.0169 (0.0053 – 0.0348)	0.0092 (0.002 – 0.15)	0.027 (0.0112 – 0.0464)	0.0275 (0.0116 – 0.0473)	0.0278 (0.0119 – 0.0479)	0.0322 (0.0138 – 0.0537)	0.0332 (0.0143 – 0.0554)	0.0285 (0.0121 – 0.0489)	0.0035 (0.0006 – 0.0088)	0.0076 (0.0024 – 0.0164)
Mortality decrease per 10,000	0.13 (0.04 – 0.34)	0.21 (0.07 – 0.49)	1.03 (0.31 – 2.2)	1.23 (0.38 – 2.52)	0.67 (0.15 – 1.67)	1.96 (0.82 – 3.37)	1.99 (0.84 – 3.43)	2.02 (0.86 – 3.47)	2.34 (1.0 – 3.89)	2.41 (1.04 – 4.02)	2.07 (0.88 – 3.54)	0.25 (0.05 – 0.64)	0.55 (0.17 – 1.19)
Prevented deaths	4 (1 - 10)	6 (2 - 15)	31 (9 - 66)	37 (11 - 76)	20 (4 - 50)	59 (25 - 101)	60 (25 - 103)	61 (26 - 104)	70 (30 - 117)	72 (31 - 121)	62 (26 - 106)	8 (1 - 19)	17 (5 - 36)
Benefits per person ($)	110 (32 - 283)	180 (60 - 410)	865 (257 - 1844)	1031 (321 - 2118)	559 (124 - 1400)	1643 (685 - 2828)	1674 (706 - 2880)	1693 (723 - 2915)	1962 (838 - 3271)	2025 (870 - 3374)	1737 (737 - 2976)	213 (39 - 537)	463 (145 - 997)
Energy cost per person ($)	26 (14 - 56)	45 (28 - 88)	26 (14 - 56)	45 (28 - 88)	0	NA	NA	NA	NA	NA	NA	0	3.3 (2.2 – 4.3)
Brand x air cleaner	NA	NA	NA	NA	NA	45 (-)	72 (60 - 102)	91 (74 - 133)	72 (60 - 102)	91 (74 - 133)	45 (-)	NA	NA
Brand y air cleaner	NA	NA	NA	NA	NA	31 (-)	57 (45 - 87)	76 (59 - 118)	57 (45 - 87)	76 (59 - 118)	31 (-)	NA	NA
Total cost per person ($)	26 (14 - 56)	45 (28 - 88)	35 (20 - 67)	53 (34 - 98)	8 (6 - 10)	NA	NA	NA	NA	NA	NA	1.6 (1.2 – 2.0)	5.7 (4.0 – 7.4)
Brand X air cleaner	NA	NA	NA	NA	NA	145 (-)	172 (159 - 202)	190 (173 - 233)	180 (166 - 212)	199 (180 - 243)	145 (-)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	176 (-)	202 (190 - 232)	221 (204 - 264)	210 (196 - 243)	229 (210 - 274)	176 (-)	NA	NA
Benefit cost ratio	4.2 (0.6 – 20.0)	4.0 (0.7 – 14.5)	25.0 (3.9 – 90.7)	19.3 (3.3 – 61.5)	67.3 (11.9 – 224.7)	NA	NA	NA	NA	NA	NA	132.9 (19.4 – 447.2)	80.9 (19.5 – 247.8)
Brand X air cleaner	NA	NA	NA	NA	NA	11.3 (4.7 – 19.5)	9.8 (3.5 – 18.1)	8.9 (3.1 – 16.8)	10.9 (4.0 – 19.6)	10.2 (3.6– 18.8)	12.0 (5.1 – 20.5)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	9.3 (3.9 – 16.1)	8.3 (3.0 – 15.2)	7.7 (2.7 – 14.3)	9.3 (3.5 – 16.7)	8.8 (3.2 – 16.1)	9.9 (4.2 – 16.9)	NA	NA
Cost per prevented death $M	2.02 (0.42 – 14.91)	2.10 (0.58 – 12.28)	0.34 (0.09 – 2.18)	0.44 (0.14 – 2.57)	0.12 (0.04 – 0.71)	NA	NA	NA	NA	NA	NA	0.06 (0.02 – 0.43)	0.1 (0.03 – 0.43)
Brand X air cleaner	NA	NA	NA	NA	NA	0.74 (0.43 – 1.78)	0.86 (0.46 – 2.40)	0.94 (0.50 – 2.71)	0.77 (0.43 – 2.12)	0.82 (0.45 – 2.35)	0.70 (0.41 – 1.66)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	0.90 (0.52 – 2.16)	1.01 (0.55 – 2.76)	1.1 (0.59 – 3.06)	0.90 (0.50 – 2.43)	0.95 (0.52 – 2.65)	0.85 (0.50 – 2.00)	NA	NA

Table S9. Results for Houston.

Houston	i1a	I1b	i2a	i2b	i3	i4	i5a	I5b	i6a	I6b	i7	i8	i9
Effective outdoor PM2.5 (μg m^{-3})	10.1 (9.9 – 10.2)	9.9 (9.6 – 10.1)	8.8 (8.1 – 9.5)	8.4 (7.6 – 9.2)	9.5 (8.9 – 10.0)	7.3 (6.8 – 7.9)	7.2 (6.7 – 7.8)	7.2 (6.7 – 7.7)	6.8 (6.4 – 7.5)	6.7 (6.2 – 7.3)	7.1 (6.6 – 7.7)	10.0 (9.6 – 10.2)	9.5 (9.0 – 9.9)
Fractional mortality reduction	0.0032 (0.0009 – 0.0075)	0.0051 (0.0017 – 0.0107)	0.0168 (0.0051 – 0.0338)	0.0206 (0.0069 - 0.0401)	0.0089 (0.0020 – 0.0221)	0.032 (0.0142 – 0.0516)	0.0328 (0.0146 – 0.0527)	0.033 (0.0150 – 0.0533)	0.0367 (0.0167 – 0.0577)	0.0378 (0.0174 – 0.0601)	0.0338 (0.0151 – 0.0541)	0.0041 (0.0008 – 0.0107)	0.0091 (0.0028 – 0.0199)
Mortality decrease per 10,000	0.18 (0.05 – 0.42)	0.28 (0.09 - 0.60)	0.94 (0.29 – 1.88)	1.15 (0.38 – 2.24)	0.49 (0.11 – 1.23)	1.79 (0.79 – 2.88)	1.83 (0.82 – 2.94)	1.84 (0.84 - 2.97)	2.05 (0.93 – 3.22)	2.11 (0.97 – 3.35)	1.88 (0.84 – 3.02)	0.23 (0.04 – 0.60)	0.51 (0.16 – 1.11)
Prevented deaths	43 (13 - 101)	69 (23 - 145)	227 (70 - 457)	278 (93 - 543)	120 (27 - 299)	433 (192 - 697)	444 (198 - 713)	447 (203 - 720)	497 (226 - 780)	512 (235 - 812)	457 (204 - 780)	56 (10 - 145)	123 (38 - 269)
Benefits per person ($)	149 (43 - 350)	238 (79 - 503)	788 (241 - 1583)	964 (322 - 1881)	415 (92 - 1036)	1501 (667 - 2417)	1539 (685 - 2471)	1549 (704 - 2497)	1721 (782 - 2703)	1774 (814 - 2816)	1582 (707 - 2703)	193 (35 - 503)	425 (133 - 933)
Energy cost per person ($)	36 (20 - 58)	62 (39 - 90)	36 (20 - 58)	62 (39 - 90)	0	NA	NA	NA	NA	NA	NA	0	3.3 (2.2 – 4.3)
Brand x air cleaner	NA	NA	NA	NA	NA	47 (-)	83 (66 - 104)	108 (85 - 137)	83 (66 – 104)	108 (85 - 137)	41 (-)	NA	NA
Brand y air cleaner	NA	NA	NA	NA	NA	31 (-)	67 (51 - 89)	93 (70 - 121)	67 (51 - 89)	93 (70 - 121)	31 (-)	NA	NA
Total cost per person ($)	36 (20 - 58)	62 (39 - 90)	44 (26 - 68)	70 (45 - 101)	8 (6 - 11)	NA	NA	NA	NA	NA	NA	1.6 (1.2 – 2.0)	5.7 (4.0 – 7.4)
Brand X air cleaner	NA	NA	NA	NA	NA	149 (-)	185 (169 - 207)	211 (188 - 239)	193 (175 - 217)	219 (194 - 249)	149 (-)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	180 (-)	216 (200 - 238)	242 (219 - 270)	225 (206 - 249)	250 (225 - 281)	180 (-)	NA	NA
Benefit cost ratio	4.1 (0.8 – 17.6)	3.9 (0.9 – 13.1)	17.7 (3.5 – 60.4)	13.7 (3.2 – 41.9)	49.2 (8.7 – 163.5)	NA	NA	NA	NA	NA	NA	120.9 (17.7 – 429.6)	74.4 (17.9 – 231.9)
Brand X air cleaner	NA	NA	NA	NA	NA	10.1 (4.5 – 16.2)	8.3 (3.3 – 14.6)	7.4 (2.9 – 13.3)	8.9 (3.6 – 15.4)	8.1 (3.3 – 14.5)	10.6 (4.7 – 17)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	8.3 (3.7 – 13.4)	7.1 (2.9 – 12.3)	6.4 (2.6 – 11.4)	7.7 (3.1 – 13.1)	7.1 (2.9 – 12.5)	8.8 (3.9 – 14.1)	NA	NA
Cost per prevented death $M	2.03 (0.48 – 11.18)	2.18 (0.64 – 9.59)	0.47 (0.14 – 2.38)	0.61 (0.20 – 2.62)	0.17 (0.05 – 0.96)	NA	NA	NA	NA	NA	NA	0.07 (0.02 – 0.48)	0.11 (0.04 – 0.47)
Brand X air cleaner	NA	NA	NA	NA	NA	0.83 (0.52 – 1.88)	1.01 (0.57 – 2.53)	1.14 (0.63 – 2.85)	0.94 (0.54 – 2.34)	1.04 (0.58 – 2.57)	0.79 (0.49 – 1.77)	NA	NA
Brand Y air cleaner	NA	NA	NA	NA	NA	1.01 (0.63 – 2.27)	1.18 (0.68 – 2.92)	1.31 (0.74 – 3.22)	1.10 (0.64 – 2.67)	1.19 (0.67 – 2.90)	0.96 (0.60 – 2.14)	NA	NA

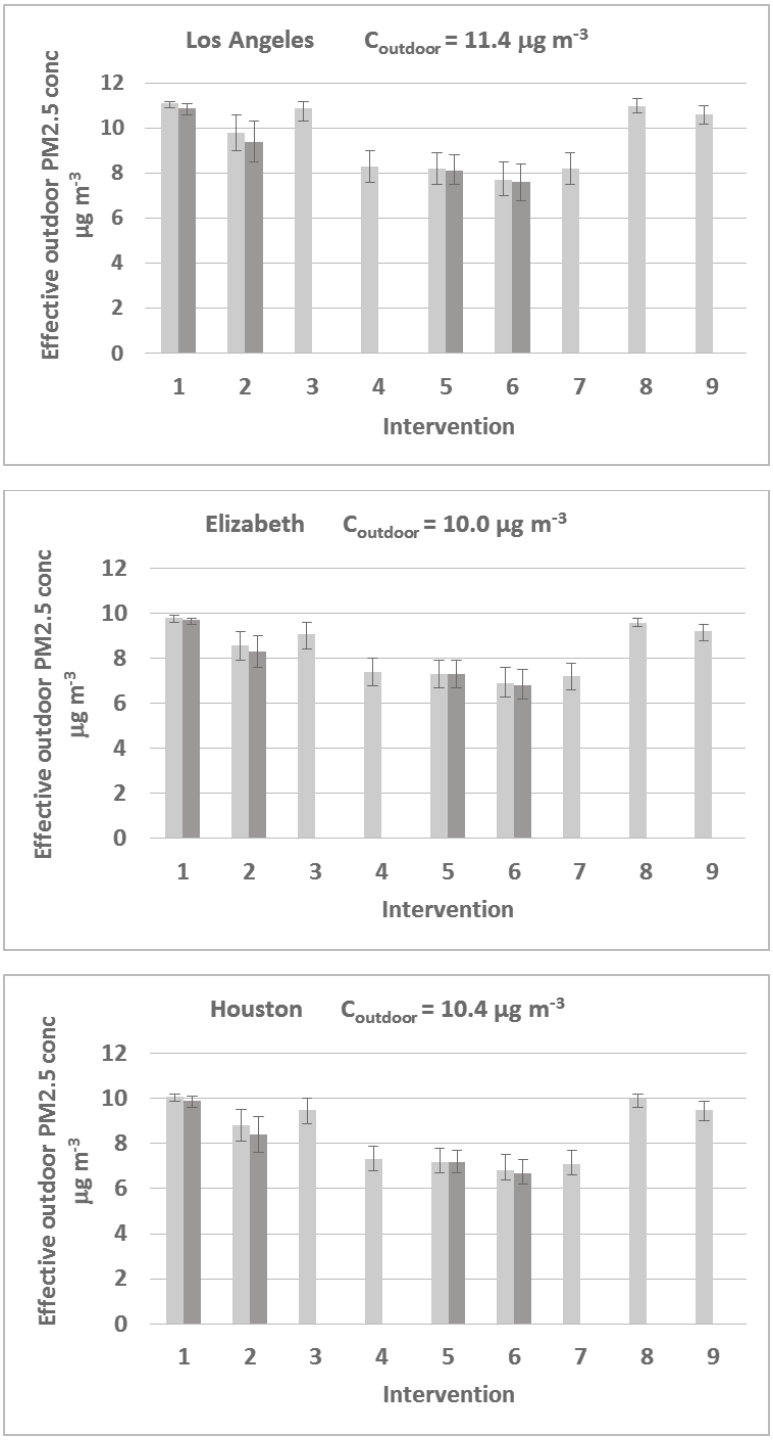

Figure S1 Effective outdoor air PM2.5 concentrations. In this figure and subsequent figures, when there are pairs of bars for an intervention the left bars depict the results of intervention 1a, 2a, 5a, and 6a and the right bars depict the results of interventions 1b, 2b, 5b and 6b.

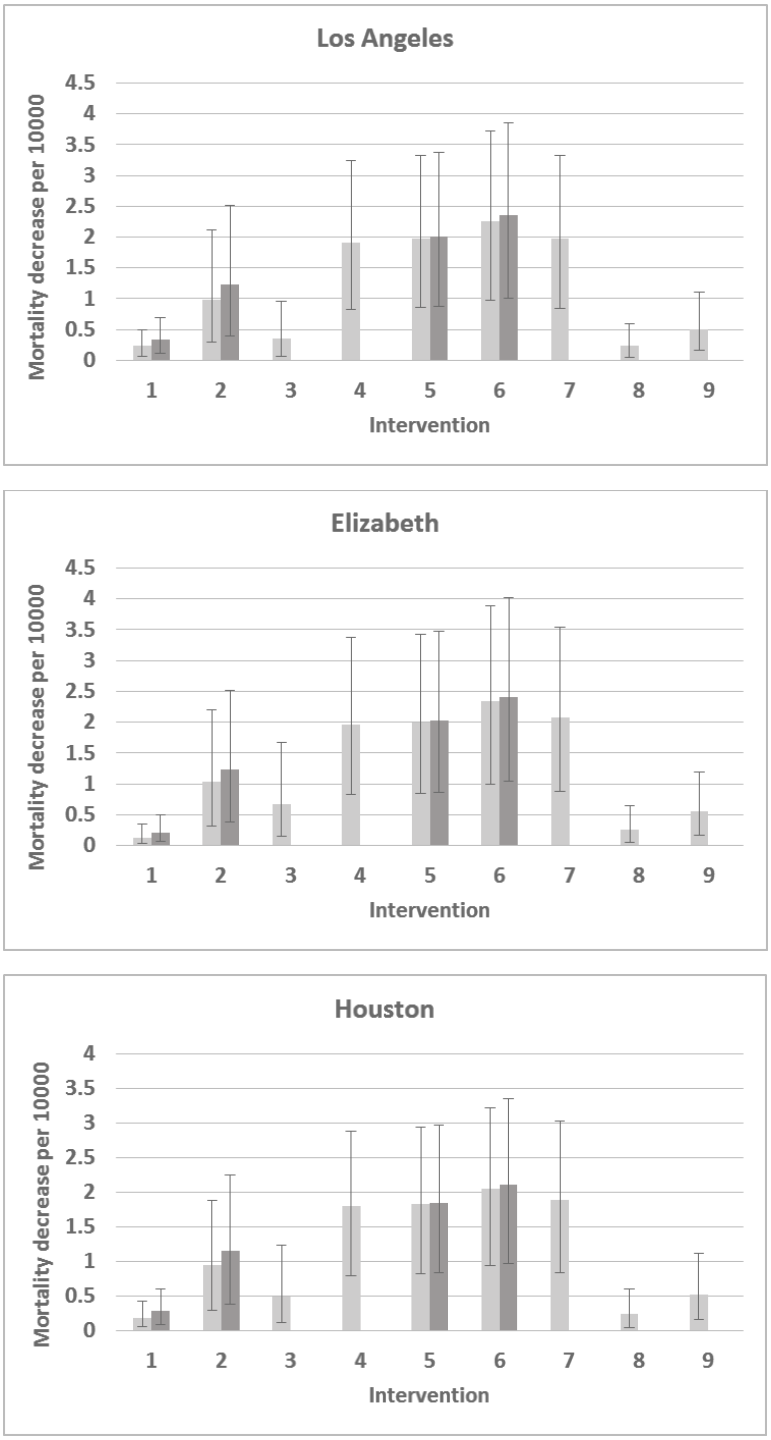

Figure S2. Mortality decrease per 10000 population.

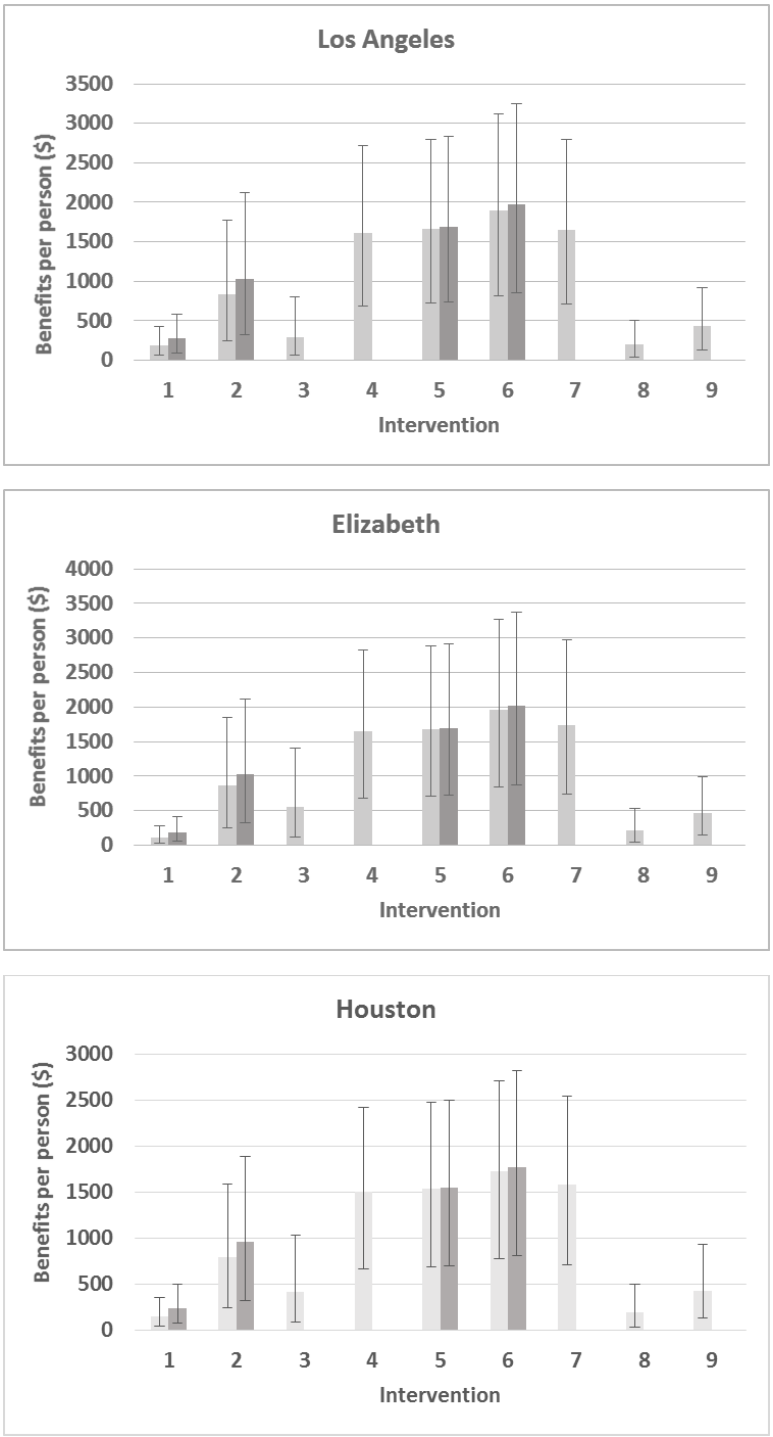

Figure S3. Economic benefits of mortality reductions.

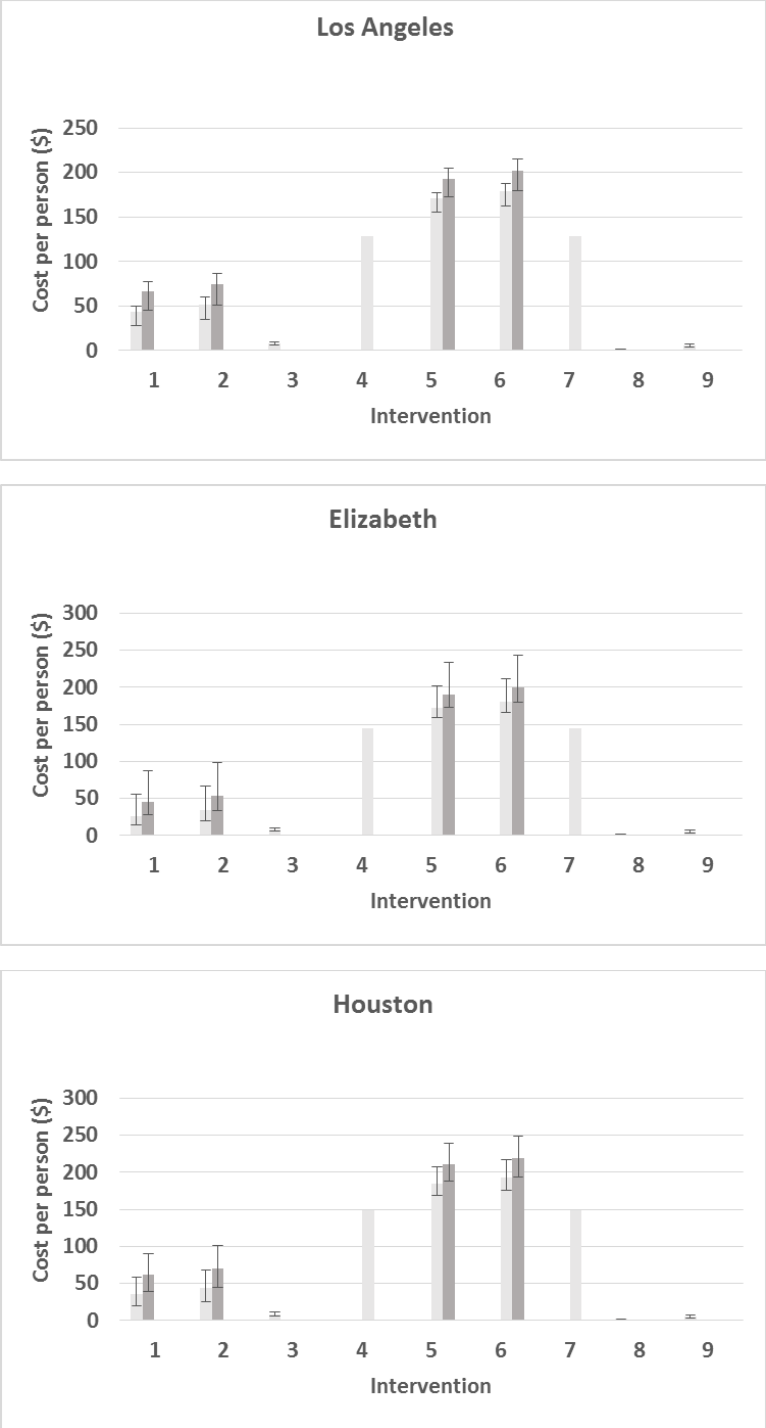

Figure S4. Intervention costs.

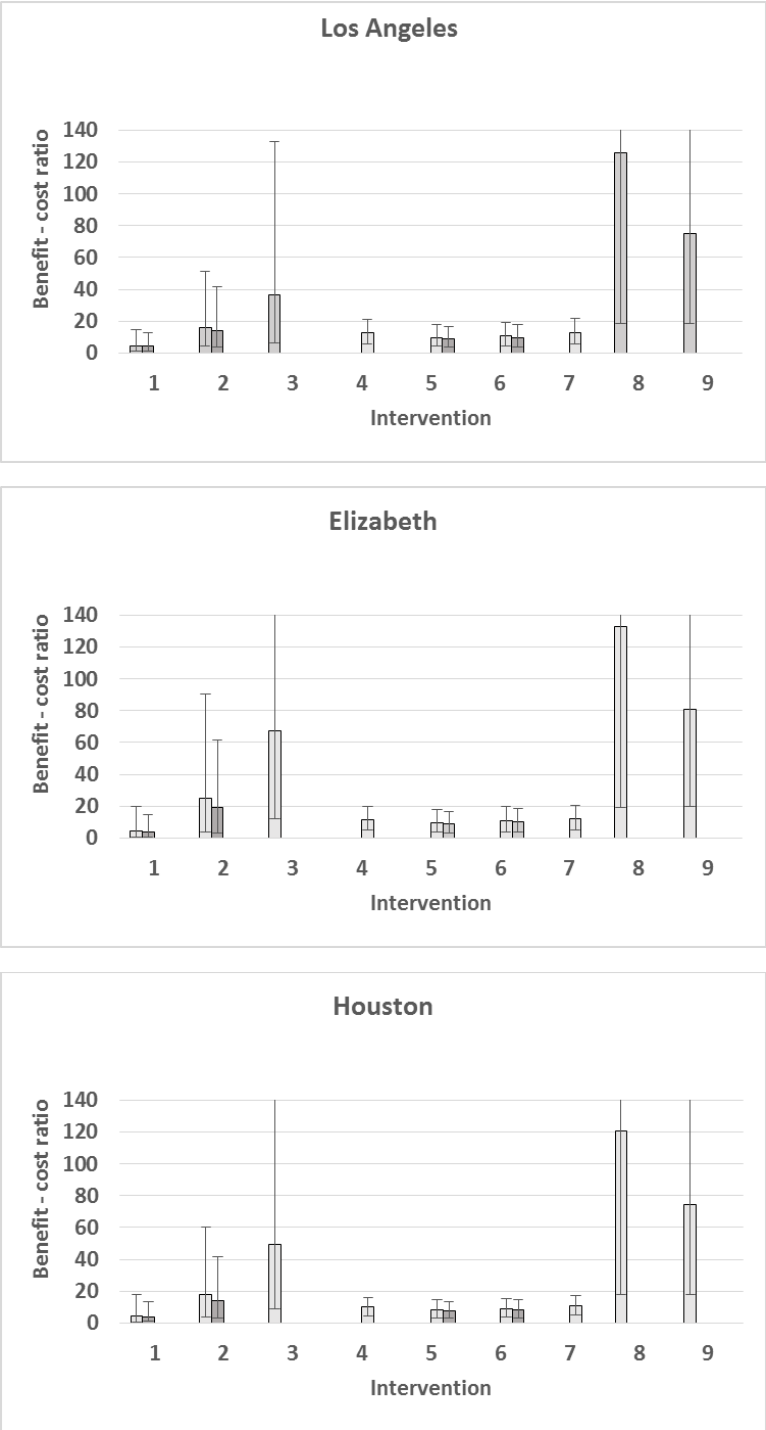

Figure S5. Benefit-cost ratios.

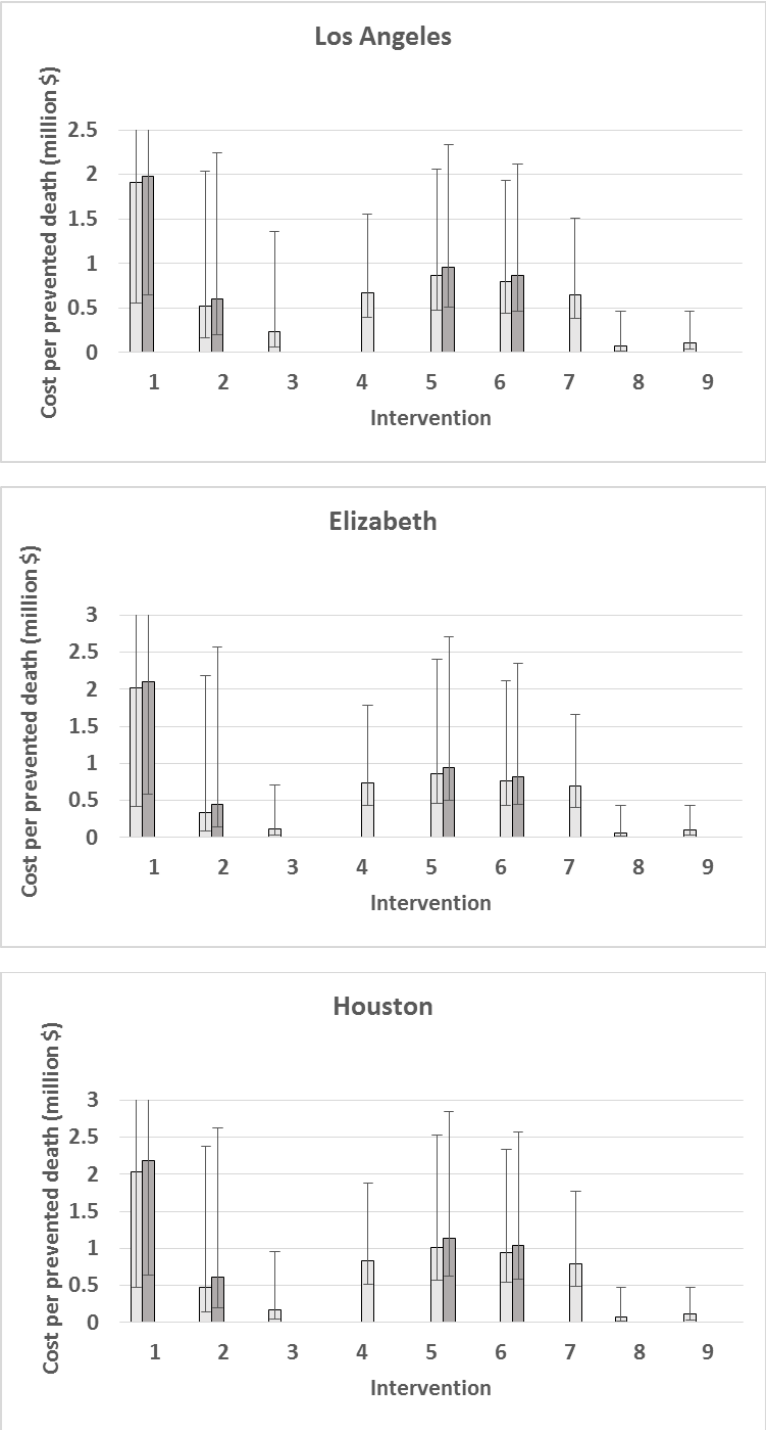

Figure S6. Costs per prevented premature death.

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