

Cost of near-roadway and regional air pollution-attributable childhood asthma in Los Angeles County

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Background: Emerging evidence suggests that near-roadway air pollution (NRP) exposure causes childhood asthma. The associated costs are not well documented.

Objective: We estimated the cost of childhood asthma attributable to residential NRP exposure and regional ozone (O₃) and nitrogen dioxide (NO₂) levels in Los Angeles County. We developed a novel approach to apportion the costs between these exposures under different pollution scenarios.

Methods: We integrated results from a study of willingness to pay to reduce the burden of asthma with results from studies of health care use and charges to estimate the costs of an asthma case and exacerbation. We applied those costs to the number of asthma cases and exacerbations caused by regional pollution in 2007 and to hypothetical scenarios of a 20% reduction in regional pollution in combination with a 20% reduction or increase in the proportion of the total population living within 75 m of a major roadway.

Results: Cost of air pollution-related asthma in Los Angeles County in 2007 was \$441 million for O₃ and \$202 million for NO₂ in 2010 dollars. Cost of routine care (care in absence of exacerbation) accounted for 18% of the combined NRP and O₃ cost and 39% of the combined NRP and NO₂ cost; these costs were not recognized in previous analyses. NRP-attributable asthma accounted for 43% (O₃) to 51% (NO₂) of the total annual cost of exacerbations and routine care associated with pollution.

Hypothetical scenarios showed that costs from increased NRP exposure might offset savings from reduced regional pollution.

Conclusions: Our model disaggregates the costs of regional pollution and NRP exposure and illustrates how they might vary under alternative exposure scenarios. The cost of air pollution is

a substantial burden on families and an economic loss for society. (*J Allergy Clin Immunol* 2014;134:1028-35.)

Key words: Air pollution, asthma, cost of illness, urban growth, vehicle emissions, willingness to pay

Approximately 36 million persons in the United States live within 300 feet of a 4-lane highway, railroad, or airport.¹ Emerging evidence suggests that near-roadway air pollution (NRP) exposure causes childhood asthma.²⁻⁵ A causal relationship implies that any subsequent asthma exacerbation, regardless of its precipitating trigger, can be attributed to NRP exposure.⁶ In urban areas in Southern California, NRP exposure might account for a substantial proportion of all air pollution-related exacerbations in children, which are commonly estimated on a population level only for regional pollutants.⁷⁻⁹

There has been little study of the costs of NRP-related health effects,^{10,11} which can be substantial.¹² There are 3 categories of costs associated with these effects: direct costs are payments for health care; indirect costs reflect opportunity costs, such as lost wages; and willingness to pay (WTP) to avoid the burden of asthma quantifies negative quality-of-life consequences.¹³ Population estimates of asthma-related costs have generally not quantified the day-to-day experience of asthma, because no robust studies had appropriately measured it.¹⁴⁻¹⁶

We developed a model of annual cost of childhood asthma that integrated novel methods from economics and epidemiology: WTP to avoid asthma morbidity¹⁷ and risk assessment for children with NRP-caused asthma.⁷ We evaluated the cost of pollution-related childhood asthma in Los Angeles County (LAC) in 2007 and the hypothetical cost per year of pollution-related childhood asthma under alternative levels of regional pollution and exposure to NRP.

LAC has a high prevalence of childhood asthma,¹⁸ dense traffic corridors, and high levels of regional air pollutants, such as ozone (O₃), nitrogen dioxide (NO₂), and particulate matter. These regional levels are expected to continue to decrease as a result of regulatory efforts.¹⁹ Although a reduction in regional pollution should decrease the cost of asthma, the net effect when that reduction is combined with a change in the proportion of the population living near a major roadway is not obvious. Based on the results of a previously published evaluation of pollution-related asthma exacerbations in LAC,⁷ we have now estimated (1) the childhood asthma-related costs attributable to regional and near-roadway pollution in 2007 and (2) the savings that might result from a 20% regional pollution reduction combined with a 20% increase or decrease in the proportion of families living in proximity to a major roadway relative to 2007 levels.⁷

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Abbreviations used

CRF: Concentration response function
ED: Emergency department
LAC: Los Angeles County
NRP: Near-roadway air pollution
NO₂: Nitrogen dioxide
O₃: Ozone
WTP: Willingness to pay

METHODS

Pollution-attributable asthma outcomes

The selection of pollutants, estimation of population exposure, concentration response functions (CRFs), and pollution-associated burden of asthma have been described previously.⁷ Briefly, we examined the effects of O₃ and NO₂ because each has a well-established causal relationship with asthma exacerbations.^{20,21} In Southern California NO₂ can be used as a proxy for general regional pollution (exclusive of O₃), including particulate matter, elemental carbon, and nitric acid, all of which are associated with respiratory health effects.^{22,23} O₃ is relatively uncorrelated with other regional pollutants in the Los Angeles air basin.^{23,24} We avoided double counting pollution-attributable exacerbations by evaluating each pollutant separately.

The baseline exposure for all scenarios was the 2007 population-weighted proportion of LAC children living near a major roadway and the 2007 levels of regional pollution.⁷ A CRF for NRP was based on residence within 75 m of a major roadway, a proxy for NRP exposure relevant for Southern California.^{5,9} Major roadways included freeways, highways, or major arterial roads (functional road classes FRC01, FRC03, and FRC04 from the TeleAtlas MultiNet roads network⁷). In the first scenario we estimated total asthma-associated costs of having 17.8% of the population living near major roadways by constructing a hypothetical in which this population's NRP exposure was reduced to background levels. We examined the costs imposed by the NO₂ and O₃ levels observed in LAC in 2007 compared with their mean values in cleaner comparison cities in the Southern California Children's Health Study that year (Scenarios 1A and 1B, respectively). The 2007 baseline measures of 24-hour NO₂ across census tracts in LAC ranged from 6.2 to 31.4 ppb (population-weighted mean, 23.3 ppb). In Scenario 1A we calculated the effect of a reduction in population-weighted NO₂ exposure to 4 ppb across all census tracts. The 2007 baseline measures of 8-hour daily maximums for O₃ across LAC ranged from 30.5 to 55.6 ppb (population-weighted mean, 39.3 ppb). In Scenario 1B we reduced the population-weighted O₃ exposure to 36.3 ppb. This first scenario generates the full asthma burden of the combined effects of NRP and regional pollution in LAC compared with that seen in cleaner communities.

To illustrate the change in costs with respect to the 2 components of pollution-attributable asthma, we constructed hypothetical scenarios in which a decrease in levels of each regional pollutant was combined with either a 20% decrease (second scenario) or a 20% increase (third scenario) in the population percentage exposed to NRP. Because 17.8% of LAC children live near a major roadway, a change of 20% constitutes 3.56 percentage points. The hypothetical reductions in NO₂ and O₃ concentrations are plausible and based on projections from the current air quality plan for Southern California.¹⁹ Health effects and their costs were estimated for a single year. When calculating outcomes in the hypothetical scenarios, we assumed that changes in the prevalence of asthma and resulting exacerbations were fully realized and instantaneous. These assumptions allowed us to compare costs across all of the scenarios and avoided the need for discounting.

For each scenario, we used the near-roadway CRF to estimate the prevalence of asthma cases attributable to NRP in a given year.⁹ We estimated 3 types of exacerbations among children in LAC for 1 year⁷: regional pollution-triggered outcomes among children with NRP-attributable asthma (Fig 1, Box 3); outcomes triggered by other factors among children with NRP-attributable asthma (Fig 1, Box 2); and regional pollution-triggered outcomes among children with asthma caused by factors other than NRP ("other-cause asthma"; Fig 1, Box 6). Asthma exacerbation-related outcomes

included bronchitis episodes, hospital admissions, emergency department (ED) visits, doctor's office visits, and school absences for respiratory illness (for O₃ only). Bronchitis, which was defined as a productive cough lasting 3 months or more, is a sensitive marker of NRP-attributable asthma exacerbations²⁵ and is distinct from viral or bacterial bronchitis. We estimated the annual frequency of each outcome attributable to these regional pollutants by using published CRFs for Southern California children when available or other appropriate CRFs when not. Tables E1-E3 in this article's Online Repository at www.jacionline.org provide details on CRFs and baseline rates.

Direct and indirect costs of an exacerbation

For each outcome, we estimated the direct cost of goods and services and the indirect cost of caregivers' lost wages. For the direct costs of health care, we used the amount charged rather than the amount paid because amounts charged are not confounded by insurance status. All costs were expressed in 2010 dollars,²⁶ and sources are summarized in Table E2.

Direct costs of hospitalization and ED visits were calculated as the sum of facilities' and physicians' charges.^{27,28} The direct cost of an office visit was estimated by using the national mean charge for a physician's office visit.²⁹ The direct cost of asthma inhalers (rescue and controller medications) was the average of the price for each inhaler category weighted by the typical use of each category.³⁰ The average price for each category of drug was the weighted mean of the name brand and generic prices.^{31,32}

The indirect costs for office visits, ED visits, and hospitalizations were the value of the caregiver's time spent traveling,³³ waiting,³⁴ and receiving care^{27,35,36} and were taken from secondary databases and peer-reviewed publications. We used 1 workday (8 hours) as the time for a school absence and valued time at the average wage rate.³⁷ Although this is the standard approach to valuing indirect costs, it overlooks the fact that caregivers of asthmatic children sometimes leave the labor force to provide care.³⁸ These caregivers face lower expected lifetime earnings even when they do return to the labor force.³⁹

Direct and indirect costs of routine care

Children with asthma need more routine care than other children. These fixed costs of asthma (Fig 1, Box 1) include medication use and treatment for excess ear and sinus infections, an asthma-related comorbidity. The expected quantity for each outcome was estimated for children aged 0 to 17 years in LAC by using the peer-reviewed literature and secondary databases (see Table E2).^{30,40,41} Costs were calculated by using the same approach as for exacerbations.

Direct and indirect costs of a bronchitis episode

Each bronchitis episode includes 5 potential costs: school absences,⁴² antibiotic prescriptions,⁴³⁻⁴⁶ office visits,^{47,48} ED visits,^{47,48} and inpatient hospital stays.^{47,48} We estimated the number of office visits, ED visits, and hospital stays as the mean rate for children with asthma using the 2007 Medical Expenditure Panel Survey. These estimates are significantly lower than some reported rates.⁴⁹

WTP

Bronchitis and asthma substantially affect quality of life.^{13,49,50} The value of this effect is quantified as the WTP to avoid this burden by using contingent valuation. A contingent valuation study offers participants a hypothetical health-related product, quotes prices, and inquires about WTP. Surveys must be designed to elicit values specific to desired health outcomes and to ensure valid responses.¹⁶ To meet these criteria, we used the results of a contingent valuation study conducted in California among families with asthmatic children.¹⁷

The WTP study¹⁷ was designed to estimate a WTP beyond the household's current expenditures and included "debriefing" questions to ensure that the WTP was based on a desire to reduce the pain and suffering of asthma. Thus the estimate is specific to asthma and additive to the other costs. The

	NRP-caused asthma	Other-cause asthma
Routine care	Controller medication	
	Comorbidities episodes	NONE
	Days with symptoms	[Box 4]
	[Box 1]	
Other-cause exacerbations	Bronchitis episodes	
	Hospital admissions	
	Emergency department visits	NONE
	Doctor's office visits	[Box 5]
	School absences	
	[Box 2]	
Regional pollution-caused exacerbations	Bronchitis episodes	Bronchitis episodes
	Hospital admissions	Hospital admissions
	Emergency department visits	Emergency department visits
	Doctor's office visits	Doctor's office visits
	School absences	School absences
	[Box 3]	[Box 6]

FIG 1. Outcomes associated with exacerbations and routine care attributable to pollution.

quality-of-life burden of a single day of symptoms was calculated as the mean WTP divided by the mean number of symptom days that would have been avoided by using the hypothetical product.¹⁷ The hypothetical product offered a 50% reduction in days with asthma symptoms, and therefore we doubled that estimate to determine the WTP to avoid a case of asthma.¹⁷

Using the WTP results,¹⁷ we calculated the quality-of-life value of symptom days for bronchitis and ear and sinus infections. We multiplied the mean number of symptom days in excess of those in children without asthma⁴¹ by the WTP to avoid a day with symptoms.¹⁷ The CRF was based on bronchitis lasting at least 3 months.²⁵ We used a more conservative value of 35 symptom days per episode based on other studies examining the cost of cough lasting more than 4 weeks.⁵⁰⁻⁵² The WTP estimate was used to assign costs to bronchitis episodes and ear and sinus infections¹⁷ because it is specific to children, is consistent with our outcome definitions, and meets the guidelines for validity.¹⁶ Our WTP estimates for these outcomes are more conservative than values extrapolated from the existing literature by the US Environmental Protection Agency.⁵³

RESULTS

We previously reported detailed estimates of the burden of pollution-attributable asthma in LAC that serve as the basis for our cost estimates.⁷ Briefly, we estimated that 27,100 cases of childhood asthma (95% CI, 4,900-51,200) are attributable to current NRP exposure, which is equivalent to 8% of the total current asthma burden in LAC. If proximity to roadways were reduced as in Scenario 2, there would be 5,900 (95% CI, 1,000-11,800) fewer cases of childhood asthma; increasing proximity as in Scenario 3 would have the exact opposite effect. [Table I](#)⁷ shows the change in the numbers of exacerbations under each scenario relative to the 2007 baseline. Among children with asthma, substantial proportions of the 2007 burden of bronchitis (57%), hospitalizations (20%), ED visits (11%), doctor's office visits (12%), and school absences (31%) were attributable to the combined effect of NRP exposure and regional pollution (Scenarios 1A and 1B in [Table I](#)). The magnitude of bronchitis episodes attributable to pollution reflects the susceptibility of the population of asthmatic children and the prevalence of asthma consequent to NRP exposure. A reduction in regional pollution and NRP exposure (Scenario 2) decreases all asthma outcomes; a reduction in regional pollution accompanied by an increase in NRP exposure (Scenario 3) increases all outcomes among those children with asthma because

of NRP. Despite the decrease in regional pollution, the increase in cases of asthma caused by NRP exposure leads to a net increase in ED visits, doctor's office visits, and school absences (Scenario 3 in [Table I](#)).

[Table II](#)^{27,33-36} shows the mean annual cost for a typical asthma case and the cost for a single bronchitis episode broken down into direct cost (column [2]), indirect cost (column [3]), and WTP (column [4]). The total annual cost of routine care (not including acute exacerbations) plus the quality-of-life cost as measured by WTP is approximately \$3,000 for a single asthma case. The cost for a single episode of bronchitis is \$1,500.

The cost per year of asthma outcomes attributable to NRP and regional pollution for each scenario is the product of the quantity of each outcome caused by pollution in that scenario ([Table I](#), column 4) and the cost of each outcome ([Table II](#), sum of columns [2], [3], and [4]). [Table III](#) shows the costs of the bronchitis episodes, hospital admissions, ED visits, doctor's office visits, and school absences (O₃ only) caused by regional air pollution for children with asthma caused by NRP (column [1]) and children with other-cause asthma (column [2]). Column (3) shows the cost of those outcomes caused by triggers other than regional pollution among children with asthma caused by NRP. The sum of the cost of these outcomes for NO₂ and exacerbation caused by other triggers among those children with NRP-attributable asthma was \$123 million ([Table III](#), row [5] and column [5]). A large portion (\$108 million) is due to bronchitis episodes brought on by pollution exposure. The cost of all outcomes among children with NRP-attributable asthma (the sum of the total row for NO₂ in column [1] of [Table III](#) [\$9 million] and the total row for NO₂ in column [3] of [Table III](#) [\$15 million]) accounted for about 20% of the \$123 million total.

The cost of outcomes caused by O₃ and exacerbations caused by other triggers among children with NRP-related asthma totaled \$362 million ([Table III](#), Scenario 1B). The differences between Scenario 1B and Scenario 1A are largely due to school absences caused by O₃. Across all O₃ outcomes, 30% of the potential savings were due to reducing exacerbations among children with NRP-attributable asthma.

Scenarios 2 and 3 in [Table III](#) illustrate the combined effects of the 20% change in NRP exposure and the 20% reduction in regional pollution. We reported the estimated costs for the regional pollutant most responsible for each outcome: NO₂ for all outcomes except school absences. Thus if regional pollution were 20% lower than 2007 levels and the proportion of the population near the roadways were reduced, there would be a decrease in the frequency of each outcome (from [Table I](#), Scenario 2) and a decrease in total costs ([Table III](#), Scenario 2) of approximately \$66 million. If the decrease in regional pollution were accompanied by an increase in NRP exposure, then there would be an increase in each outcome that is triggered by regional air pollution or other factors among those with NRP-attributable asthma (from [Table I](#), Scenario 3, columns [1] and [3], in brackets to indicate an increase in disease burden). The total increase in costs would be \$24 million ([Table III](#), Scenario 3, columns [1] plus [3]). There would be a decrease in outcomes among those children with other-cause asthma (from [Table I](#), Scenario 3, column [2]) and consequently a decrease in costs of \$43 million ([Table III](#), Scenario 3, column [2]). The net decrease in the total cost of all exacerbations in Scenario 3 would be \$20 million. The exacerbations caused by factors other than air pollution among children with NRP-attributable asthma (column [3]) account for most of the large difference between Scenarios 2

TABLE I. Decrease (increase in brackets) in the number of asthma outcomes under different exposure scenarios relative to baseline NRP exposure and regional pollution

	Decrease (increase in brackets) in outcomes attributable to regional air pollution among those with asthma caused by:			Decrease (increase in brackets) in outcomes due to other causes among those with asthma caused by NRP	Total decrease (increase in brackets) in outcomes (1)+(2)+(3)
	NRP (1)	Other factors (2)	Both NRP and other factors (1)+(2)	(3)	(4)
Scenario 1A: Reduction in NRP exposure and regional NO ₂ levels to background levels					
Bronchitis episodes	5,600	59,500	65,100	5,100	70,200
95% CI	660-12,100	20,500-85,700	22,500-92,800	900-11,700	31,000-95,700
Hospital admissions	30	340	375	235	610
95% CI	5-65	265-420	295-450	50-450	410-840
ED visits	35	370	405	1,570	1,970
95% CI	5-85	65-670	75-725	320-2,970	690-3,400
Doctor's office visits	870	9,200	10,100	19,800	29,900
95% CI	70-2,140	1,900-16,500	2,000-17,900	4,100-37,700	12,300-48,900
Scenario 1B: Reduction in NRP exposure and regional O ₃ levels to background levels					
Bronchitis episodes	1,610	17,200	18,800	9,100	27,800
95% CI	0-4,050	530-32,100	590-34,900	1,900-17,600	9,100-44,300
Hospital admissions	1.9	20.7	22.6	270	290
95% CI	0.3-4.2	10-31.7	10.9-34.3	50-510	80-530
ED visits	11	121	133	1,590	1,730
95% CI	2-23	75-167	84-181	330-3,020	460-3,160
Doctor's office visits	59	632	692	20,600	21,300
95% CI	6-144	160-1,111	175-1,207	4,200-39,100	4,800-39,800
School absences	27,900	302,000	329,900	86,200	416,100
95% CI	449-70,600	43,800-562,300	47,700-612,100	12,000-168,700	140,200-681,500
Scenario 2: Decrease in proportion of children living near major roadways and 20% reduction in regional pollution					
Bronchitis episodes (NO ₂)	340	17,600	17,900	2,000	19,900
95% CI	30-820	4,800-29,300	4,900-29,900	400-4,100	6,900-31,700
Hospital admissions (NO ₂)	1	75	80	60	135
95% CI	0-3	60-95	60-95	10-120	90-200
ED visits (NO ₂)	2	80	80	350	430
95% CI	0-4	15-145	15-150	70-700	140-790
Doctor's office visits (NO ₂)	40	2,020	2,060	4,500	6,600
95% CI	0-100	400-3,620	410-3,700	860-9,030	2,530-11,310
School absences (O ₃)	350	18,710	19,050	24,400	43,400
95% CI	0-930	970-36,510	980-37,120	980-46,800	14,350-71,760
Scenario 3: Increase in proportion of children living near major roadways and 20% reduction in regional pollution					
Bronchitis episodes (NO ₂)	[339]	17,929	17,589	[2,009]	15,580
95% CI	[33]-[824]	4,875-29,879	4,769-29,273	[382]-[4,042]	2,288-27,758
Hospital admissions (NO ₂)	[1]	79	77	[58]	19
95% CI	[3]-0	62-96	60-94	[11]-[116]	[42]-70
ED visits (NO ₂)	[2]	81	80	[352]	[272]
95% CI	[4]-0	15-148	14-145	[67]-[703]	[630]-19
Doctor's office visits (NO ₂)	[39]	2,059	2,020	[4,519]	[2,499]
95% CI	[3]-[100]	411-3,697	403-3,629	[859]-[9,037]	[7,305]-1,552
School absences (O ₃)	[349]	19,194	18,846	[24,367]	[55,21]
95% CI	[930]-0	988-37,354	968-36,649	[968]-[46,818]	[34,370]-23,222

Estimates are reproduced from Perez et al⁷ and baseline outcomes, population and concentration-response functions are reported there. The baseline for each scenario is 2007 levels of NRP exposure and regional pollution. Scenario 1 is a 17.8 percentage point decrease in NRP exposure (to background levels of zero), decrease of 19.3 ppb of NO₂ (Scenario 1A), and decrease of 3.03 ppb of O₃ (Scenario 1B). Scenario 2 corresponds to a 3.56 percentage point decrease in NRP exposure, decrease of 3.9 ppb of NO₂, and decrease of 0.61 ppb of O₃ relative to the 2007 baseline. Scenario 3 corresponds to a 3.56 percentage point increase in NRP exposure, decrease of 3.9 ppb of NO₂, and decrease of 0.61 ppb of O₃ relative to the 2007 baseline. Values within brackets are an increase in the number of outcomes.

and 3 (a reduction of \$23 million per year in Scenario 2 and an increase of almost that amount in Scenario 3).

For each scenario, Table IV shows the sum of the costs of exacerbations (column [1], which is the sum of columns [1], [2], and [3] in Table III) and routine care for NRP-attributable asthma cases (column [2]). Scenarios 1A and 1B in Table IV reflect the total burden of NRP and regional pollution beyond that of cleaner comparison communities. A 100% reduction in major roadway

proximity with a reduction in NO₂ levels to those in clean communities (Scenario 1A) would save approximately \$203 million annually. Elimination of NRP proximity and reduction of O₃ to clean community levels (Scenario 1B) would save almost \$441 million yearly. In Scenario 1A 39% of the total cost of the current burden of NRP and regional NO₂ concentrations is due to the cost of routine care for NRP-attributable asthma cases (the analogous figure for O₃ is 18%). These NRP fixed costs

TABLE II. Costs of routine asthma care for a single case of asthma and costs of a single bronchitis episode (in 2010 US dollars)

	Annual cost for routine asthma case				Annual cost per asthma case (1)*(2+3+4)
	Mean annual occurrence (1)	Direct cost per occurrence (2)	Indirect costs per occurrence* (3)	WTP (4)	
Quality of life	1	NA	NA	1,549	1,549
Medication					
Inhaled corticosteroid	2.19	125	NA		273
Cromolyn	1.07	95	NA		102
Albuterol	6.81	55	NA		374
Comorbidities					
Doctor's office visits (nonurgent)	0.85	113	43		133
Mean cost of antibiotics	2.21	85	NA		189
Urgent care visits	0.22	113	43		34
Hospital admissions	0.03	6,646	505		215
Days with symptoms	3.85			17	65
Total cost per year					2,934

	Cost for a typical bronchitis episode				Mean cost per bronchitis episode (1)*(2+3+4)
	Mean occurrence per bronchitis episode (1)	Direct cost per occurrence (2)	Indirect cost per occurrence* (3)	WTP per day (4)	
Doctor's office visits	1.15	113	43		179
ED visits	0.06	844	107		57
Hospital admissions	0.01	16,625	747		174
School absences	2.00	NA	220		440
Antibiotics	1.16	85	NA		99
Days with symptoms	35	NA	NA	17	595
Total cost per episode					1,544

NA, Not applicable.

*Mean times were as follows: 46.6 minutes for roundtrip travel for medical purpose,³³ 23 minutes waiting for office visit,³⁴ 24 minutes for receiving care,³⁵ 3.16 hours for visiting the ED,³⁶ and 2.2 days for an asthma admission and 3.3 days for a bronchitis admission.²⁷

have not been considered in previous regulatory risk assessments. The total cost savings achieved by reducing both regional pollution and proximity exposure (Scenario 2) are approximately \$84 million; in comparison, increasing NRP exposure while reducing regional pollution provides a cost savings of only \$2 million (Scenario 3). Thus Scenario 3 suggests that the cost of the increased number of asthma cases due to NRP-attributable asthma eliminates almost all the savings of reducing regional pollution.

The asthma-related effect of NRP is the sum of the cost of all exacerbations among children with NRP-attributable asthma (columns [1] and [3] from Table III) and the cost of routine care for NRP-attributable cases (column [2] from Table IV). Thus if NRP exposure were eliminated, \$104 and \$189 million could be saved, respectively, by also reducing NO₂ and O₃ levels to levels seen in clean communities.

DISCUSSION

The cost of air pollution-attributable childhood asthma is large, between \$203 million (for NO₂) and \$441 million (for O₃) in 2007. For perspective, that was 6% and 13%, respectively, of the health department's total expenditures on all health services for uninsured residents in LAC.⁵⁴ A 20% decrease in regional pollution accompanied by a 20% decrease in the proportion of children living near major roads would reduce the cost of asthma by approximately \$81 million more than if that decrease in regional pollution were accompanied by a 20% increase in the proportion of the population living near major roads. If policies such as replacing automobiles with electric vehicles or creating buffers between major roadways and children's homes and schools are effective in eliminating cases of asthma attributable to traffic proximity exposure, the reduction

in the total cost of the combined pollution-attributable burden would be 51% for NO₂ and 43% for O₃.

Expenditures to cover the direct costs of asthma represent a loss to society. In Los Angeles 32% of children are covered by public insurance (Medi-Cal or Healthy Families)⁵⁵; therefore public funds pay for 32% of the direct pollution-attributable costs of asthma (\$34 million a year for NO₂). If this public expenditure were eliminated, that money could be used to extend Medi-Cal insurance to an additional 33,700 children each year (based on the cost of coverage and average health care expenditures⁵⁶). Two doses of varicella vaccinations could be provided to an additional 135,218 children each year.⁵⁷ If we invested the recovered funds in education, then full-time preschool could be provided for an additional 2,358 children, producing a societal benefit of \$49 to \$132 million a year (based on returns to investment in early education⁵⁸).

Our methodology relied on 2 key assumptions. First, we assumed that without exposure to NRP, the child would not have had asthma. Some of these children might have nonetheless had asthma as a result of other risk factors, which would render our costs an overestimation. Second, we assumed that the CRF of proximity would be the same under alternative hypothetical scenarios, but the effects of traffic proximity as a proxy for NRP are likely to decrease if average vehicle emissions decrease in the future.

There are additional uncertainties in estimating costs. Based on the previously estimated burden of disease,⁷ we accounted for statistical uncertainty. Actual prices charged for health care vary over individuals; thus we used average estimates of charges. We also assumed that an NRP-attributable asthma case requires the same level of routine care and treatment for comorbidities as asthma of other causes. We assumed an instantaneous change in

TABLE III. Decrease (increase in brackets) in annual costs of exacerbations of childhood asthma under various scenarios (in thousands of 2010 US dollars)

	Decrease (increase in brackets) in cost of exacerbations due to regional air pollution among children with asthma caused by:			Decrease (increase in brackets) in cost of exacerbations due to other causes among children with asthma caused by NRP (3)	Decrease (increase in brackets) in total cost of exacerbations (1) + (2) + (3)
	NRP (1)	Other factors (2)	All factors (1) + (2)		
Scenario 1A: Reduction in NRP exposure and regional NO ₂ levels to background levels					
Bronchitis episodes	8,646	91,868	100,514	7,874	108,389
95% CI	1,019-18,636	31,652-132,321	34,740-143,283	1,390-18,065	47,864-147,761
Hospital admissions	398	4,516	4,980	3,121	8,101
95% CI	66-863	3,519-55,778	3,918-5,976	664-5,976	5,445-11,156
ED visits	33	352	385	1,493	1,873
95% CI	5-81	62-637	71-689	304-2,824	656-3,233
Doctor's office visits	136	1,434	1,574	3,086	4,660
95% CI	11-334	296-2,572	312-2,790	639-5,876	1,917-7,622
Decrease in cost in Scenario 1A	9,213	98,170	107,453	15,574	123,023
95% CI	1,101-19,914	35,529-191,308	39,041-152,738	2,997-32,741	55,882-169,772
Scenario 1B: Reduction in NRP exposure and regional O ₃ levels to background levels					
Bronchitis episodes	2,486	26,510	29,012	14,050	42,923
95% CI	0-6,258	823-49,522	908-53,898	2,934-27,174	14,050-68,399
Hospital admissions	25	275	300	3,586	3,851
95% CI	4-56	133-421	145-465	644-6,773	1,062-7,039
ED visits	10	115	126	1,512	1,645
95% CI	2-22	71-159	80-172	314-2,872	437-3,005
Doctor's office visits	9	99	108	3,211	3,320
95% CI	1-22	25-173	27-188	655-6,094	748-6,203
School absences	20,785	224,981	245,766	64,216	309,982
95% CI	335-52,595	32,630-418,897	35,535-455,996	8,940-125,677	104,445-507,697
Decrease in cost in Scenario 1B	23,315	251,980	275,312	86,575	361,721
95% CI	342-58,953	33,682-469,172	36,695-510,719	13,487-168,590	120,742-592,343
Scenario 2: Decrease in proportion of children living near major roadways and 20% reduction in regional pollution					
Bronchitis episodes (NO ₂)	525	27,174	27,638	3,088	30,726
95% CI	46-1,266	7,411-45,239	7,566-46,166	618-6,330	10,654-48,945
Hospital admissions (NO ₂)	13	996	1,062	797	1,793
95% CI	0-40	797-1,262	797-1,262	133-1,594	1,195-2,656
ED visits (NO ₂)	2	76	76	333	409
95% CI	0-4	14-138	14-143	67-666	133-751
Doctor's office visits (NO ₂)	6	315	321	701	1,029
95% CI	0-16	62-564	64-577	134-1,407	394-1,763
School absences (O ₃)	261	13,938	14,192	18,177	32,332
95% CI	0-693	723-27,199	730-27,653	730-34,865	10,690-53,459
Decrease in cost in Scenario 2	807	42,499	43,289	23,096	66,289
95% CI	46-2,019	9,007-74,402	9,171-75,801	1,682-44,862	23,066-107,574
Scenario 3: Increase in proportion of children living near major roadways and 20% reduction in regional pollution					
Bronchitis episodes (NO ₂)	[523]	27,682	27,157	[3,102]	24,056
95% CI	[51]-[1,272]	7,527-46,133	7,363-45,198	[590]-[6,241]	3,533-42,858
Hospital admissions (NO ₂)	[13]	1,049	1,023	[770]	252
95% CI	[40]-0	823-1,275	797-1,248	[146]-[1,541]	[558]-930
ED visits (NO ₂)	[2]	77	76	[335]	[259]
95% CI	[4]-0	14-141	13-138	[64]-[668]	[18]-[599]
Doctor's office visits (NO ₂)	[6]	321	315	[704]	[389]
95% CI	[16]-0	64-576	63-566	[134]-[1,409]	[242]-[1,139]
School absences (O ₃)	[260]	14,299	14,040	[18,153]	[4,113]
95% CI	[693]-0	736-27,828	721-27,302	[721]-[34,878]	[17,300]-[25,065]
Decrease (increase in brackets) in cost in Scenario 3	[804]	43,428	42,611	[23,064]	19,547
95% CI	[51]-[2,025]	9,164-75,953	8,957-74,452	[1,655]-[44,737]	[24,368]-61,348

The baseline was 2007 exposure to NRP and NO₂ and O₃ levels. Scenario 1 was a 17.8 percentage point decrease in NRP exposure (to background levels of 0). Scenario 1A was a decrease of 19.3 ppb of NO₂, and Scenario 1B was a 3.03 ppb decrease of O₃. Scenario 2 was a 3.56 percentage point decrease in NRP exposure with decreases of 3.9 ppb of NO₂ and 0.61 ppb of O₃. Scenario 3 was a 3.56 percentage point increase in NRP exposure with decreases of 3.9 ppb of NO₂ and 0.61 ppb of O₃. Values within brackets are increases in cost. Values might not sum because of rounding.

asthma prevalence, but if the change occurred over a lengthy time frame those costs would need to be appropriately discounted.

We assumed that outcomes associated with NO₂ and O₃ might affect the same subjects, and we did not sum the costs associated

with each of these pollutants. In addition, some studies suggest that exposure to NO₂ might potentiate the effect of O₃⁵⁹ or that prior O₃ exposure might exacerbate the effects of NRP in diesel exhaust.⁶⁰ Therefore these estimates would underestimate costs

TABLE IV. Decrease (increase in brackets) in the annual total costs of pollution-attributable asthma relative to baseline (in millions of 2010 US dollars)

	Decrease in cost (increase in brackets) of pollution-attributable exacerbations (1)	Decrease in cost (increase in brackets) of routine care for asthma caused by NRP (2)	Decrease in total cost (increase in brackets) (1) + (2)
Scenario 1A			
100% Reduction in proportion of children living near major roadways and reduction of NO ₂ levels to the background level of clean communities	123	80	203
95% CI	56-170	14-150	70-320
Scenario 1B			
100% Reduction in proportion of children living near major roadways and reduction of O ₃ levels to the background level of clean communities	362	80	441
95% CI	121-592	14-150	135-743
Scenario 2			
20% Reduction in proportion of children living near major roadways and 20% reduction in regional pollution	66	17	84
95% CI	23-108	3-35	26-142
Scenario 3			
20% Increase in proportion of children living near major roadways and 20% reduction in regional pollution	20	[17]	2
95% CI	[24]-61	[3]-[35]	[27]-27

Values within brackets are increases in costs. In scenarios 2 and 3 the pollution change is for NO₂ for all outcomes, except for school absences, for which we used O₃. The cost of routine care is the cost for a case (Table II) multiplied by the change in the number of cases attributable to NRP exposure (decrease of 27,100 for Scenarios 1A and 1B, increase of 5,900 for Scenario 2, and decrease of 5,900 for Scenario 3). Values might not sum because of rounding.

if the effects were additive. Lastly, we might have underestimated the total costs of pollution-related asthma because we omitted the costs associated with adult asthma.

In conclusion, by properly accounting for the effects of both NRP and regional pollution on asthma exacerbations, we identified large and previously unappreciated costs. Disaggregating the effects of regional pollution and NRP exposure helps clarify the health co-benefits and cost savings that could be achieved by reducing exposure to both regional and near-roadway pollution. Although our results are specific to LAC, they are relevant to other large metropolitan areas because of the large numbers of children living near major roadways across the United States.^{1,2,61}

Key messages

- The annual cost of asthma in LAC attributable to O₃ is approximately \$441 million, and the annual cost attributable to NO₂ is approximately \$202 million.
- Routine care for children with asthma attributable to NRP was 18% of the combined NRP and O₃ cost and 39% of the combined NRP and NO₂ cost.
- The cost of NRP accounted for 51% of the total asthma-related cost due to NRP and regional NO₂ and 43% of the total due to NRP and O₃.
- The cost of routine asthma care was almost \$3,000/y for each child.
- The actual public expenditures in 2007 on the asthma-related burden of pollution could have provided public insurance to 33,000 children, 135,000 varicella vaccinations, or full-time preschool for 2,000 children.

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ONLINE SUPPLEMENT

Table 1: Source of Odds Ratios for Estimates of Health Effects¹

Health effect	Pollutant	OR ² (95% CI)	Study details	Source
Asthma prevalence	NRP ³	1.64 (1.10, 2.44)	Age 5-7 years, 12 communities in Southern California	McConnell et al. (2006)
Bronchitis episodes	NO ₂	1.070 per 1 ppb (1.020, 1.130)	24-hr mean, age 9-13 years, 12 communities in Southern California	McConnell et al. (2003)
Bronchitis episodes	O ₃	1.060 per 1 ppb (1.000, 1.120)	1000-1800-hr mean, age 9-13 years, 12 communities in Southern California	McConnell et al. (2003)
Emergency room visits	NO ₂	1.0011 per 1 ppb (1.0002, 1.0021)	24-hr max, age 0-15 years, 4 cities in Europe (Sunyer); 1-hr max, age 2-18 years, Atlanta, GA (Peel)	Mean of Sunyer et al. (1997); Peel et al. (2005)
Emergency room visits	O ₃	1.0024 per 1 ppb (1.0015, 1.0033)	1-hr max, meta-analysis of prior literature	Ostro et al. (2006)
Hospital admissions	NO ₂	1.079 per 14 ppb (1.054, 1.090)	24-hr mean, age 0-18 years, Hong Kong	Lee et al. (2006)
Hospital admissions	O ₃	1.00240 per 1 ppb (1.00161, 1.00317)	8-hr mean, age 0-18 years, Hong Kong; 8-hr mean, age 0-17 years, New York state	Mean of Lee et al. (2006); Lin et al. (2008)
Doctor visits	NO ₂	1.0025 per 1 ppb (1.0005, 1.0045)	24-hr mean, age 0-14 years, London	Hajat et al. (1999)
Doctor visits	O ₃	1.0011 per 1 ppb (1.0003, 1.0018)	24-hr mean, age 3-15, Santiago, Chile	Ostro et al. (1999)
School absences	O ₃	1.031 per 1 ppb (1.002, 1.060)	1000-1800-hr mean, fourth graders (typically ages 9-10 years), 12 communities in Southern California	Gilliland et al. (2001)

1. Table is reproduced from Perez et al. (2012).

2. Published values of odds ratios were transformed to value per 1 ppb. In estimating the number of outcomes, we applied the correction $\frac{OR}{[1+F(OR-1)]}$ from Zhang and Yu (1998) where F is the frequency in the population and OR is the odds ratio. Effects were estimated for 8-hr daily max, and CRFs for other exposure times were converted using appropriate ratios.

3. Residence within 75m was used as the proxy for near-roadway pollution (NRP). Major roadways defined as functional road class FRC01, FRC03 or FRC04 from TeleAtlas MultiNet roads network.

Table 2: Source for Frequency and Costs of Outcomes**A. Outcomes of asthma exacerbations attributable to regional pollution**

	Source for Frequency of Outcome	Source for Cost Estimates
<u>Outcome</u>		
Emergency room visits	Perez et al. (2012)	HCUPnet (2011) for ICD-9 493 & AAP (2007/2008)
Hospitalizations	Perez et al. (2012)	HCUPnet (2011) for ICD-9 493 & AAP (2007/2008)
Asthma office visits	Perez et al. (2012)	MEPS (2004)
School days absent	Perez et al. (2012)	US Census Bureau (2013)
Symptom days	CHIS (2009)	Brandt et al. (2012)
<u>Bronchitis episodes</u>		
	Perez et al. (2012) for number of bronchitis episodes attributable to regional pollution. Frequency of outcomes per bronchitis episode as noted below.	
Doctor visits	MEPS (2007) for ICD-9 490/491 among those children diagnosed with asthma	MEPS (2004)
Emergency room visits	MEPS (2007) for ICD-9 490/491 among those children diagnosed with asthma	HCUPnet (2011) for ICD-9 490/491 AAP (2007/2008)
Hospitalizations	MEPS (2007) for ICD-9 490/491 among those children diagnosed with asthma	HCUPnet (2011) for ICD-9 490/491 AAP (2007/2008)
School absences	Oeffinger et al. (1997)	US Census Bureau (2013)
Antibiotics	Mean of frequency of antibiotic prescription for bronchitis reported in: Coco and Mainou (2005); Evertsen et al. (2010); Gonzales and Sande (2000); Nyquist et al. (1998). Frequency of use of each antibiotic types for respiratory infection from Steinman et al. (2003)	Epocrates (2010)
Symptom days	Chang and Glomg (2006); Chang et al. (2010); Bisagaard and Szeffler (2007); McConnell et al. (2003)	Brandt et al. (2012)

B. Outcomes of asthma cases attributable to traffic proximity

	Source for Frequency of Outcome	Source for Cost Estimates
<u>Asthma cases attributable to NRP</u>	Perez et al. (2012)	Compiled based on frequency and costs of outcomes for representative case as described below

Asthma medication per case/year

Controller inhalers	Mean number of controller inhalers used from CHIS (2009). Frequency of types of controllers from Kattan et al. (2005)	Epocrates (2010)
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Rescue inhalers	Mean number of inhalers from Kattan et al. (2005)	Epocrates (2010)
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Comorbidities per case/year

Non-urgent office visits	Frequency of comorbidities among asthmatics from Grupp-Phelan et al. (2001). Frequency of outcomes due to comorbidity from Grupp-Phelan et al. (2001)	MEPS (2004)
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Antibiotics		Epocrates (2010)
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Urgent care visits		MEPS (2004)
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Inpatient days		HCUPnet (2011) & AAP (2007/2008)
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C. Time associated with outcomes

Time category	Source for travel time	Time on site (wait plus service time)
Office visit (all cause)	NHTS (2009)	Greek et al. (2006); Cabana et al. (2006)
Emergency room (all cause)	NHTS (2009)	Pitts et al. (2008)
Hospital (asthma-specific)	NHTS (2009)	HCUPnet (2011) for ICD-9 493
Hospital (bronchitis-specific)	NHTS (2009)	HCUPnet (2011) for ICD-9 490/491

Table 3: Baseline Rates and Data Used to Calculate Frequency of Outcomes¹

Outcome	Baseline rate	Value	Reference
Susceptible population	Children ages 0-17 years in 2007	2,549,722	US Census Bureau 2011
Asthma case	Asthma prevalence	0.1257	McConnell et al. (2006)
Bronchitis episodes	Fraction of children with asthma reporting episodes per year	0.387	McConnell et al. (2003)
Hospital admissions	Number of yearly hospital admissions for asthma (ICD-9 493)	3,131	California Breathing; Milet et al. (2007)
Emergency room visits	Number of yearly ER visits for asthma (ICD-9 493)	18,658	California Breathing; Milet et al. (2007)
Doctor visits	Fraction of children with asthma reporting doctor visits per year	0.751	McConnell (2011) ²
School absences	Mean daily school absence rate for respiratory illness among children with asthma	0.0158	Gilliland et al. (2001)
Pollution Exposure			
Near-roadway pollution	Percentage of LA county population living within 75m of major road	17.8%	TeleAtlas MultiNet roads network
Regional NO ₂	Annual NO ₂ population-weighted concentration (ppb) in 2007	23.3 ppb	US EPA Air Quality System
Regional O ₃	8-hr max O ₃ population-weighted concentration (ppb) in 2007	39.3 ppb	US EPA Air Quality System

1. Table is reproduced from Perez et al. (2012).

2. Based on answer to the question, “Has your child ever been to a doctor for wheezing?” among those that have ever had wheezing or whistling.

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