Air Pollution from Truck Traffic and Lung Function in Children Living near Motorways

Bert Brunekreef,[1] Nicole A. H. Janssen,[2] Jeroen de Hartog,[1] Hendrik Harssema,[2] Mirjam Knape,[2] and Patricia van Vliet[2]

The contribution of motorized traffic to air pollution is widely recognized, but relatively few studies have looked at the respiratory health status of subjects living near busy roads. We studied children in six areas located near major motorways in the Netherlands. We measured lung function in the children, and we assessed their exposure to traffic-related air pollution using separate traffic counts for automobiles and trucks. We also measured air pollution in the children's schools. Lung function was associated with truck traffic density but had a lesser association with automobile traffic density. The association was stronger in children living closest (<300 m) to the motorways. Lung function was also associated with the concentration of black smoke, measured inside the schools, as a proxy for diesel exhaust particles. The associations were stronger in girls than in boys. The results indicate that exposure to traffic-related air pollution, in particular diesel exhaust particles, may lead to reduced lung function in children living near major motorways. (Epidemiology 1997;8:298–303)

Keywords: air pollution, motorized traffic, lung function, child, nitrogen dioxide, black smoke, automobiles, trucks, diesel.

Motorized traffic is a major source of air pollutants such as nitrogen dioxide (NO_2) and suspended particulate matter.[1,2] Yet, relatively few studies have looked at the health of subjects living near busy roads. The prevalence of respiratory symptoms was found to be elevated among subjects living near busy roads in five studies.[3–7] Two case-control studies found that hospitalizations for wheezing bronchitis among children 4–48 months old, and for asthma among children less than 5 years old, respectively, were related to measures of traffic density[8,9]; air pollution exposure was not measured in either of these studies. Some studies have relied on distance of home address from major roads.[5,9] Others have used self-reported traffic density.[6,7] Two studies modeled NO_2 concentrations.[4,8] One study used density of traffic on the main road through school districts.[3] The absence of objective measurements of lung function in all but one study is another limitation.

In this study, we evaluated the extent to which lung function in children living near motorways is related to air pollution generated on the motorway. We measured lung function in schoolchildren living near major motorways in the Netherlands. We assessed the precise location of home and school for each child. We also measured air pollution in the classrooms of the children. For each motorway, separate traffic counts were available for automobile and truck traffic.

Methods

Study Locations

We chose six areas with homes located close to major motorways in Dordrecht, Rotterdam-Ommoord, Rotterdam-Overschie, Voorburg, Delft, and Leiderdorp. In 1993, these motorways carried between 80,000 and 152,000 vehicles per day.

Population

We approached schools in the spring of 1995. Of 20 schools approached, 13 participated (Dordrecht, 3 of 3; Rotterdam-Ommoord, 4 of 4; Rotterdam-Overschie, 2 of 5; Voorburg, 1 of 2; Delft, 1 of 3; Leiderdorp, 2 of 3). The reasons for which schools declined participation were not related to the exposure variables under study. Nonparticipating schools were located at distances from the motorways similar to those of participating schools. All 1,498 children in grades 4–7 (ages 7–12 years) were asked to participate, and informed consent forms were distributed to their parents. Of these, 1,242 children (82.9%) agreed, and each child then received a questionnaire. Eventually, 1,068 questionnaires (71.3%) containing usable data were returned. We carried out lung function testing on 1,191 children (79.5%); 1,092 of these children were able to perform an acceptable

From the Departments of [1]Epidemiology and Public Health and [2]Air Quality, University of Wageningen, Wageningen, The Netherlands.

Address correspondence to: Bert Brunekreef, Department of Epidemiology and Public Health, University of Wageningen, P.O. Box 238, 6700 AE Wageningen, The Netherlands.

Supported by a grant from the Department of the Environment of the Province of South Holland.

Submitted July 16, 1996; final version accepted December 6, 1996.

TABLE 1. Description of Sites

Location (Motorway)	Traffic Density (/24 Hours)		Number of Children Studied	Distance (m) of Homes to Motorway	
	Trucks	Automobiles		Median	5th Percentile
Leiderdorp (A4)	8,098	72,878	129	258	75
Voorburg (A12)	8,444	132,292	120	318	63
Ommoord (A20)	12,118	88,868	279	404	110
Delft (A13)	12,531	119,376	95	456	260
Overschie (A13/A20)	12,593/16,771	119,966/135,694	109	189	23
Dordrecht (A16)	17,580	91,615	145	300	27

lung function test according to European Community for Coal and Steel (ECCS) criteria.[10] Ultimately, lung function and/or questionnaire data were obtained from 1,213 children (81.0%).

Most of the children lived within 1,000 m from the motorway. We restricted the data analysis to these children, as it is unlikely that air pollution levels at greater distances were influenced much by motorway traffic. Of all 1,092 children with a valid lung function test, 877 lived within 1,000 m of the motorway. Of these, 778 also had usable questionnaire data. The 99 children who had no questionnaire data were not different in lung function from the children with full lung function and questionnaire data.

Table 1 shows the distribution of the 877 children over the six areas. Table 2 shows some characteristics of the study population. Most children (85%) had lived at their current address for at least 3 years.

Air Pollution Exposure

We assessed exposure to traffic-related air pollution in the following ways:

1. We measured the distance (in meters) of home and school to the motorway on 1:1,000 scale maps. Rotterdam-Overschie is located on both sides of the A13 motorway and on one side of the A20 motorway; the other areas are located on one side of the motorway.

2. We ascertained traffic density. We used weekday counts of motorway traffic for 1993 to classify traffic density on the motorways.[11] Counts have been increasing over time, with 1993/1985 ratios ranging from 1.30 in Rotterdam-Overschie to 1.68 in Voorburg.

3. In 12 of the 13 participating schools, indoor measurements were conducted of particles less than 10 μm in aerodynamic diameter (PM_{10}) and NO_2. PM_{10} was measured with low-volume impactors operating at 10 liters per min.[12,13] NO_2 was measured with Palmes' tubes.[14] Reflectance of PM_{10} filters was measured using the Organisation for Economic Cooperation and Development (OECD) method for black smoke (BS) to measure the "blackness" of the indoor particles.[15] Outdoor side-by-side measurements of reflectance of PM_{10} filters and filters exposed according to the OECD method showed excellent agreement (correlation = 0.94), so we converted the reflectance of the indoor PM_{10} filters into BS concentrations. PM_{10} equipment was operated on timers set to sample air only when the children were in school. Although measurements were conducted for 2 months in each school, measurements were conducted in all schools simultaneously only in June. The June measurements were consequently used in all further analyses.

We used wind direction data obtained from Rotterdam airport to evaluate the percentage of time that schools had been downwind of the motorway (in a 120° sector surrounding the perpendicular line connecting the school to the motorway) during indoor air pollution measurements and during or preceding lung function tests.

TABLE 2. Characteristics of Study Population (N = 877)

Characteristic	Percentage or Mean (Standard Deviation)
Gender (% boys)	50.1
Age (years)	9.39 (1.27)
Height (cm)	143.0 (9.3)
Weight (kg)	34.1 (8.4)
FVC (liters)	2.410 (0.479)
FEV_1 (liters)	2.108 (0.395)
PEF (liters/sec)	4.889 (1.073)
$MEF_{25-75\%}$* (liter/sec)	2.446 (0.634)
Smoking in the home (%)	50.3
Living in damp home (%)	32.0
Pets in the home (%)	59.0
Parental education high/medium/low (%)	35.9/38.0/25.8
Gas cooking (%)	84.5
Unvented, gas-fired water heater (%)	21.9

* $MEF_{25-75\%}$ = maximal expiratory flow, midexpiratory phase.

Lung Function

We measured lung function at the schools, following ECCS procedures,[10] between May 23 and July 7, 1995. We used Vicatest-5 rolling-seal spirometers. For each child, at least three acceptable maneuvers had to be obtained. A detailed description of the method was published previously.[16] We measured the height and weight of the children in stockinged feet. Measurements in Dordrecht and Rotterdam-Overschie occurred on and after days with winds coming from the motorway. In the other four areas, schools were generally upwind from the motorway during and on the 3 days before lung function measurements.

Potential Confounders

Information on potential confounders was collected by questionnaire. We inquired about age (in years), gender, parental respiratory symptoms (yes/no), smoking in the

 Epidemiology May 1997, Volume 8 Number 3

TABLE 3. Air Pollution Levels Measured in Schools Located near Dutch Motorways

Location and School	BS ($\mu g/m^3$)	NO_2 ($\mu g/m^3$)	% of Time Downwind of Motorway during Measurements	Distance of School from Motorway (m)
Leiderdorp				
Le1	8.81	9.2	14.5	393
Le2	6.73	13.0	14.5	300
Voorburg				
Vo1	8.21	23.6	32.4	121
Ommoord				
Om1	6.73	14.8	16.6	318
Om2	5.15	9.2	16.6	298
Om3	5.74	14.7	16.6	645
Om4			16.6	450
Delft				
De1		16.0	17.1	394
Overschie				
Ov1	12.37	32.8	43.6	35
Ov2	10.59	27.7	43.6	83
Dordrecht				
Do1	20.78	30.0	46.1	168
Do2	12.47	22.0	46.1	125
Do3	11.97	21.5	46.1	300

home (yes/no), presence of pets (yes/no), damp or mold stains in the home (yes/no), ethnicity (Dutch/non-Dutch), number of persons in the household, gas cooking (yes/no), gas-fired, unvented water heaters (yes/no), and socioeconomic status (highest level of education attained by the parent completing the questionnaire).

Data Analysis

We used a log transformation to normalize residuals for lung function, height, weight, and age.[17] We employed multiple linear regression to investigate the relation between air pollution exposure and lung function. Truck traffic density and automobile traffic density were uncorrelated on the investigated motorways, because the motorways near the Rotterdam port carry a high proportion of truck traffic, whereas the motorways near The Hague (seat of government) carry relatively few trucks. We analyzed both types of traffic jointly in the multiple regression analysis. We evaluated the distance variable "home within 100 m" in the same model. The correlation between BS and NO_2 in schools was high (>0.70); we evaluated these two variables separately. We adjusted all analyses for the potential confounders mentioned earlier, with the exception of parental respiratory symptoms, which could also have been influenced by air pollution from traffic. We therefore evaluated this variable in separate analyses. To investigate effect modification by distance, we restricted some analyses to children living within 300 m from the motorway. Stratified analyses were also conducted by gender, ethnicity, truck traffic density, and number of years in the area. We used partial residual plots to investigate to what extent outlying observations were influencing the results unduly. We expressed results as percentage difference in lung function over ranges of 10,000 trucks per day, 50,000 cars per day, and 10 μg per m^3 for both black smoke and NO_2, and as percentage difference between children living within and beyond 100 m from the motorway. Analyses were conducted with SAS software, version 6.10.[18]

Results

Air Pollution Exposure

As shown in Table 1, the median distance of the homes of participating children was smallest in Rotterdam-Overschie and greatest in Delft. In Dordrecht and Rotterdam-Overschie, many children lived within 100 m of the motorway.

There was a 2.2-fold range in the number of trucks passing each weekday, from 8,098 in Leiderdorp to 17,580 in Dordrecht. Automobile traffic density ranged from 73,000 in Leiderdorp to 136,000 in part of Rotterdam-Overschie.

Schools were located close to the motorway in Rotterdam-Overschie, Dordrecht, and Voorburg (Table 3). Indoor concentrations of BS and NO_2 in the schools are shown in Table 3. PM_{10} concentrations in the schools were highly variable and higher than those measured outdoors, confirming earlier experiences with in-school measurements of PM_{10}.[19] This finding probably reflects resuspension of particles stemming from activity of the children. In contrast, BS concentrations derived from the PM_{10} filters were comparable with outdoor concentrations and much less variable over time. Owing to equipment failure, we obtained no particle data in the Delft school. There was a fourfold range in mean BS and NO_2 concentrations among schools. We examined the relation of the school concentrations with distance from the motorway, truck traffic density (for BS), total traffic density (for NO_2), and percentage of time downwind from the motorway. BS concentrations were related to truck traffic density and percentage of time downwind, but not to distance from the motorway. NO_2 was related primarily to total traffic density and percentage of time downwind.

Air Pollution Exposure and Lung Function

Table 4 shows that, for all children living within 1,000 m of the motorways, truck traffic density was related to forced expiratory volume in 1 second (FEV_1), peak expiratory flow (PEF), and forced expiratory flow, midexpiratory phase ($FEF_{25-75\%}$). The estimated effects ranged from −2.5% for FEV_1 to −8.0% for PEF, per 10,000 trucks. The coefficients for BS, automobile traffic density, and NO_2 ($FEF_{25-75\%}$ only) tended to be negative also. After restriction of the analysis to children living within 300 m, the estimated effects of truck traffic den-

TABLE 4. Percentage Change* (and 95% Confidence Limits) in Lung Function in Children Living near Motorways, by Air Pollution Exposure Variables, and Adjusted for Potential Confounders

Exposure Variable	FVC	FEV_1	PEF	$FEF_{25-75\%}$
All children living within 1,000 m of motorway†				
Home within 100 m (*vs* home at >100 m)	0.4 (−2.2, 3.0)	0.2 (−2.4, 3.0)	−1.7 (−5.8, 2.6)	−1.1 (−6.6, 4.7)
Density of truck traffic (per 10,000)	−2.0 (−5.0, 0.8)	−2.5 (−5.3, 0.4)	−8.0 (−12.2, −3.6)	−5.3 (−11.0, 0.7)
Density of automobile traffic (per 50,000)	0.8 (−1.1, 2.8)	0.3 (−1.8, 2.3)	3.1 (−0.2, 6.5)	−2.1 (−6.3, 2.2)
BS concentration in school (per 10 $\mu g/m^3$)	−0.6 (−3.1, 2.0)	−1.2 (−3.8, 1.5)	−2.6 (−6.7, 1.6)	−2.2 (−7.5, 3.4)
NO_2 concentration in school (per 10 $\mu g/m^3$)	0.2 (−1.0, 1.4)	−0.3 (−1.5, 1.0)	0.7 (−1.3, 2.8)	−1.9 (−4.5, 0.8)
Children living within 300 m of motorway‡				
Density of truck traffic (per 10,000)	−3.6 (−7.4, 0.3)	−4.1 (−7.9, −0.1)	−7.7 (−13.4, −1.7)	−4.0 (−11.6, 4.4)
Density of automobile traffic (per 50,000)	2.1 (−0.7, 5.1)	0.5 (−2.3, 3.4)	−0.8 (−5.1, 3.6)	−5.0 (−10.4, 0.8)
BS concentration in school (per 10 $\mu g/m^3$)	−2.7 (−6.1, 0.9)	−3.7 (−7.2, −0.2)	−5.8 (−11.1, −0.2)	−6.3 (−13.2, 1.2)
NO_2 concentration in school (per 10 $\mu g/m^3$)	−0.3 (−2.0, 1.5)	−1.2 (−2.9, 0.6)	−1.3 (−4.0, 1.4)	−3.6 (−7.1, −0.1)

* Adjusted for age, height, weight, gender, smoking in the home, presence of pets, damp or mold stains in the home, ethnicity, number of persons in the household, gas cooking, gas-fired, unvented water heaters, and parental education.
† N = 689 in multiple regression analysis; 605 for analysis with BS.
‡ N = 308 in multiple regression analysis.

sity on forced vital capacity (FVC) and FEV_1, BS on all lung function parameters, and automobile traffic density and NO_2 on $FEF_{25-75\%}$ increased. Additional adjustment for parental respiratory symptoms did not change the findings. The results of the stratified analysis for gender in Table 5 show that the estimated effects of truck traffic density were stronger in girls than in boys.

Figure 1 shows estimated mean levels of FEV_1 for each of the six areas, for children living within 300 m from the motorways, after adjustment for confounders. The figure shows a clear exposure-response relation.

Other stratified analyses showed little effect modification. There was an indication that children living within 100 m of the motorways in the areas most exposed to truck traffic (Dordrecht and Rotterdam-Overschie) had poorer lung function than children living farther away.

Discussion

We consider the participation rate of 81% of eligible children to be satisfactory. The areas most exposed to truck traffic (Dordrecht and Rotterdam-Overschie) had the lowest response (73–74%), and the least exposed area (Leiderdorp) had the highest response (96%). We consider it unlikely that this relatively small difference could have biased the results. A within-Dordrecht comparison of results between schools with different response rates confirmed this view: the school in Dordrecht with the highest response rate also had the highest air pollution exposure, and lung function of children going to this school was lower than lung function of the children in the other Dordrecht schools.

It is unlikely that the results of the lung function tests were biased. Tests were performed at school without parents being present, using two investigators and two spirometers in all schools. At the time of the tests, the investigators were unaware of traffic counts and of the results of air pollution measurements. We calculated distances from homes and schools to the motorways after lung function had been measured.

Children in Dordrecht and Rotterdam-Overschie, but not in the other four locations, were examined on days with wind coming from the motorway. It is therefore possible that the effect on lung function could have been acute.[20–24] To evaluate this possibility, repeated observa-

TABLE 5. Percentage Change* (and 95% Confidence Limits) in Lung Function in Children Living near Motorways, by Air Pollution Exposure Variables, and Adjusted for Potential Confounders, for Boys and Girls Separately

	FVC	FEV_1	PEF	$FEF_{25-75\%}$
Boys living within 1,000 m of motorway (N = 351)				
Density of truck traffic (per 10,000)	0.4 (−3.4, 4.3)	−1.2 (−5.0, 2.8)	−8.1 (−13.9, −2.0)	−5.0 (−12.8, 3.6)
BS school concentration (per 10 $\mu g/m^3$)	3.9 (0.2, 7.7)	1.4 (−2.4, 5.3)	−0.5 (−6.6, 6.0)	−3.4 (−11.0, 5.0)
Girls living within 1,000 m of motorway (N = 338)				
Density of truck traffic (per 10,000)	−3.6 (−7.7, 0.6)	−3.4 (−7.5, 0.9)	−7.0 (−13.0, −0.6)	−5.4 (−13.6, 3.5)
BS concentration in school (per 10 $\mu g/m^3$)	−4.4 (−7.9, −0.8)	−3.8 (−7.4, −0.1)	−4.6 (−10.1, 1.2)	−2.3 (−9.7, 5.7)
Boys living within 300 m of motorway (N = 162)				
Density of truck traffic (per 10,000)	−1.1 (−6.7, 4.9)	−1.8 (−7.5, 4.2)	−9.7 (−17.8, −0.7)	−0.8 (−12.4, 12.3)
BS concentration in school (per 10 $\mu g/m^3$)	3.6 (−1.9, 9.5)	1.9 (−3.8, 8.0)	−2.5 (−11.2, 7.0)	−2.4 (−13.6, 10.1)
Girls living within 300 m of motorway (N = 146)				
Density of truck traffic (per 10,000)	−6.3 (−11.4, −0.8)	−6.2 (−11.5, −0.6)	−6.1 (−13.9, 2.4)	−7.0 (−17.5, 4.7)
BS concentration in school (per 10 $\mu g/m^3$)	−8.4 (−12.9, −3.6)	−8.3 (−13.0, −3.4)	−7.8 (−14.7, −0.3)	−8.9 (−18.2, 1.5)

* Adjusted for age, height, weight, smoking in the home, presence of pets, damp or mold stains in the home, ethnicity, number of persons in the household, gas cooking, gas-fired, unvented water heaters, and parental education.

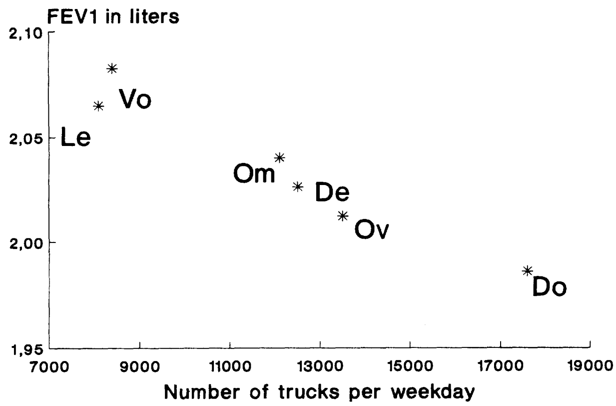

FIGURE 1. Association between truck traffic density and forced expiratory volume in 1 second (FEV_1) in children living <300 m from a motorway, adjusted for age, gender, smoking in the home, presence of pets, damp or mold stains in the home, ethnicity, number of persons in the household, gas cooking, gas-fired, unvented water heaters, and parental education. *Le* = Leiderdorp; *Vo* = Voorburg; *Om* = Ommoord; *De* = Delft; *Ov* = Overschie; *Do* = Dordrecht.

tions of lung function on days with different wind directions are needed.

At school, children were exposed to similar levels of air pollution during the daytime, when concentrations of traffic-related air pollutants are highest. This aggregation effect probably explains why differences in lung function were more pronounced between areas than within areas.

The effects that we estimated were larger than those reported from Munich,[3] perhaps because of the more precise exposure classification in our study. The only other study relating respiratory health indicators with truck traffic[6] relied on self-reported traffic density.

Occupational studies have provided some evidence that exposure to diesel exhaust is associated with chronic respiratory effects,[25–27] but results of these studies have been inconsistent. Most occupational studies have been cross-sectional, and selection effects may have occurred. Also, the studies were conducted almost exclusively among males. Ulfvarson *et al* observed acute changes in lung function among ferry crew members exposed to diesel exhaust[28] and found them to be related primarily to diesel exhaust particles.[29]

Studies on chronic effects of air pollution on lung function of children have focused on the comparison of random samples of children between communities with different levels of air pollution.[30,31] These studies did not allow comparison of subjects living close to busy roads with subjects living further away.

The predominance of the associations in girls is intriguing. Others[4,8,32] have found similar differences between boys and girls. Effects of "passive smoking" on lung function were found to be stronger in boys than in girls in some studies.[33,34] Such effects, however, may be related primarily to prenatal exposure.

Diesel powered vehicles have much larger emissions of particles than gasoline-powered vehicles.[35] Per km driven, the emission of submicronic particles by heavy-duty diesel trucks may be 100 times greater than the emission of a catalyst-equipped, gasoline-powered automobile. Diesel exhaust particles contain large amounts of elemental carbon (EC), which contributes much to the "blackness" of particles as measured by the OECD method for BS. A side-by-side comparison of BS and EC measured near a busy road in Berlin, Germany, in 1991 found a close relation (R^2 = 0.96).[36] Apparently, BS measurements represent diesel exhaust particles (as opposed to tire abrasion, which results in organic carbon) well in such situations.

Oberdorster *et al*[37] have recently hypothesized that submicronic particles have a role in the effects of fine particulate matter air pollution on health. Diesel engines emit large numbers of ultrafine particles, and the number of submicronic particles has been shown to be influenced by traffic close to busy roads.[38] Long-term exposure to submicronic particles is therefore likely to be increased in subjects living close to busy roads, especially those roads carrying many diesel-powered trucks.

A separate analysis of the respiratory symptom data collected in the study has shown that truck traffic density and black smoke concentrations were also associated with increased reporting of chronic respiratory symptoms [van Vliet P, Knape M, de Hartog J, Janssen NAH, Harssema H, Brunekreef B. Air pollution from road traffic and chronic respiratory symptoms in children living near motorways (submitted for publication)].

References

1. Health Effects Institute. Air Pollution, the Automobile, and Public Health. Washington DC: National Academy Press, 1988.
2. Hildemann LM, Markowski GR, Cass GR. Chemical composition of emissions from urban sources of fine organic aerosol. Environ Sci Technol 1991;25:744–759.
3. Wjst M, Reitmeir P, Dold S, Nicolai T, Von Loeffelholz Colberg E, Von Mutius E. Road traffic and adverse effects on respiratory health in children. BMJ 1993;307:596–600.
4. Oosterlee A, Drijver M, Lebret E, Brunekreef B. Chronic respiratory symptoms of children and adults living along streets with high traffic density. Occup Environ Med 1996;53:241–247.
5. Nitta H, Sato T, Nakai S, Maeda K, Aoki S, Ono M. Respiratory health associated with exposure to automobile exhaust. I. Results of cross-sectional studies in 1979, 1982 and 1983. Arch Environ Health 1993;48:53–58.
6. Weiland SK, Mundt KA, Ruckmann A, Keil U. Self reported wheezing and allergic rhinitis in children and traffic density on street of residence. Ann Epidemiol 1994;4:243–247.
7. Nakatsuka H, Watanabe T, Ikeda M, Hisamichi S, Shimizu H, Fujisaku S, Ichirowatari Y, Konno J, Kuroda S, Ida Y, Suda S, Kato K. Comparison of the health effects between indoor and outdoor air pollution in Northeastern Japan. Environ Int 1991;17:51–59.
8. Pershagen G, Rylander E, Norberg S, Eriksson M, Nordvall SL. Air pollution involving nitrogen dioxide exposure and wheezing bronchitis in children. Int J Epidemiol 1995;24:1147–1153.
9. Edwards J, Walters S, Griffiths RK. Hospital admissions for asthma in pre-school children: relationship to major roads in Birmingham, United Kingdom. Arch Environ Health 1994;49:223–227.
10. Quanjer PH, Tammeling GJ, Cotes JE, Pedersen OF, Peslin R, Yernault JC. Standardized lung function testing. Eur Respir J 1993;6(suppl16):5–40.
11. Department of Public Works. Transportation of Goods. Yearly Report 1993 (in Dutch). ISSN 1381–6918. Rotterdam: Department of Public Works, 1995.
12. Lioy PJ, Wainman T, Turner W, Marple VA. An intercomparison of the indoor air sampling impactor and the dichotomous sampler for a 10-μm cut size. J Air Pollut Control Assoc 1988;38:668–670.
13. Marple VA, Rubow KL, Turner W, Spengler JD. Low flow rate sharp cut impactors for indoor air sampling: design and calibration. J Air Pollut Control Assoc 1987;37:1303–1307.

14. Palmes ED, Gunnison AF, DiMattio J, Tomczyk C. Personal sampler for nitrogen dioxide. Am Ind Hyg Assoc J 1976;37:570–577.
15. Organisation for Economic Cooperation and Development. Methods of Measuring Air Pollution: Report of the Working Party on Methods of Measuring Air Pollution and Survey Techniques. Paris: Organisation for Economic Cooperation and Development, 1964.
16. Houthuijs D, Remijn B, Brunekreef B, de Koning R. Estimation of maximum expiratory flow volume variables in children. Pediatr Pulmonol 1989;6:127–132.
17. Dockery DW, Berkey CS, Ware JH, Speizer FE, Ferris BG Jr. Distribution of forced vital capacity and forced expiratory volume in one second in children 6–11 years of age. Am Rev Respir Dis 1983;128:405–412.
18. SAS Institute. The SAS System for Windows. Cary, NC: SAS Institute, 1994.
19. Janssen NAH, Hoek G, Harssema H, Brunekreef B. A relation between personal and ambient PM10. Epidemiology 1995;6:S45.
20. Hoek G, Brunekreef B. Acute effects of a winter air pollution episode on pulmonary function and respiratory symptoms of children. Arch Environ Health 1993;48:328–335.
21. Hoek G, Brunekreef B. Effects of low level winter air pollution on respiratory health of Dutch children. Environ Res 1994;64:136–150.
22. Roemer W, Hoek G, Brunekreef B. Effect of wintertime air pollution on respiratory health of children with chronic respiratory symptoms. Am Rev Respir Dis 1993;147:118–124.
23. Pope CA III, Dockery DW. Acute health effects of PM10 pollution on symptomatic and non-symptomatic children. Am Rev Respir Dis 1992;145:1123–1128.
24. Pope CA III, Dockery DW, Spengler JD, Raizenne ME. Respiratory health and PM10-pollution. Am Rev Respir Dis 1991;144:668–674.
25. Gamble JF, Jones WG. Respiratory effects of diesel exhaust in salt miners. Am Rev Respir Dis 1983;128:389–394.
26. Gamble J, Jones W, Minshall S. Epidemiological-environmental study of diesel bus garage workers: chronic effects of diesel exhaust on the respiratory system. Environ Res 1987;44:6–17.
27. Ames RG, Reger RB, Hall DS. Chronic respiratory effects of exposure to diesel emissions in coal mines. Arch Environ Health 1984;39:389–394.
28. Ulfvarson U, Alexandersson R, Aringer L, Svensson E, Hedenstierna G, Hogstedt C, Holmberg G, Rosen G, Sorsa M. Effects of exposure to vehicle exhaust on health. Scand J Work Environ Health 1987;13:505–512.
29. Ulfvarson U, Alexandersson R. Reduction in adverse effect on pulmonary function after exposure to filtered diesel exhaust. Am J Ind Med 1990;17:341–347.
30. Dockery DW, Speizer FE, Stram DO, Ware JH, Spengler JD, Ferris BG Jr. Effects of inhalable particles on respiratory health of children. Am Rev Respir Dis 1989;139:587–594.
31. Raizenne M, Neas LM, Damokosh AI, Dockery DW, Spengler JD, Koutrakis P, Ware JH, Speizer FE. Health effects of acid aerosols on North-American children: pulmonary function. Environ Health Perspect 1996;104:506–514.
32. Forastière F, Corbo GM, Pistelli R, Micjelozzi P, Anabiti N, Brancato G, Ciappi G, Perucci CA. Bronchial responsiveness in children living in areas with different air pollution levels. Arch Environ Health 1994;49:111–118.
33. Cunningham J, Dockery DW, Speizer FE. Maternal smoking during pregnancy as a predictor of lung function in children. Am J Epidemiol 1994;139:1139–1152.
34. Cuijpers CEJ, Swaen GMH, Wesseling G, Sturmans F, Wouters EFM. Adverse effects of the indoor environment on respiratory health in primary school children. Environ Res 1995;86:11–23.
35. Hildemann LM, Markowski GR, Jones MC, Cass GR. Submicrometer aerosol mass distributions of emissions from boilers, fireplaces, automobiles, diesel trucks, and meat-cooking operations. Envir Sci Technol 1991;14:138–152.
36. Ulrich E, Israël GW. Diesel soot measurement under traffic conditions. J Aerosol Sci 1992;23(suppl 1):S925–S928.
37. Oberdorster G, Gelein RM, Ferin J, Weiss B. Association of particulate air pollution and acute mortality: involvement of ultrafine particles. Inhalation Toxicol 1995;7:111–124.
38. Ruoss K, Karg E, Brand P. Short term variations of size distributions and concentrations of atmospheric aerosol particles. J Aerosol Sci 1991;22:S629–632.