Personal and Outdoor Nitrogen Dioxide Concentrations in Relation to Degree of Urbanization and Traffic Density

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To assess differences in exposure to air pollution from traffic in relation to degree of urbanization and traffic density, we measured personal and home outdoor nitrogen dioxide (NO₂) concentrations for 241 children from six different primary schools in the Netherlands. Three schools were situated in areas with varying degrees of urbanization (very urban, fairly urban, and nonurban) and three other schools were located near highways with varying traffic density (very busy, fairly busy, and not busy). Weekly averaged measurements were conducted during four different seasons. Simultaneously, indoor and outdoor measurements were conducted at the schools. Personal and outdoor NO₂ concentrations differed significantly among children attending schools in areas with different degrees of urbanization and among children attending schools in areas close to highways with different traffic densities. For the children living near highways, personal and outdoor NO₂ concentrations also significantly decreased with increasing distance of the home address to the highway. Differences in personal exposures between children from the different schools remained present and significant after adjusting for indoor sources of NO₂. This study has shown that personal and outdoor NO₂ concentrations are influenced significantly by the degree of urbanization of the city district and by the traffic density of and distance to a nearby highway. Because NO₂ can be considered a marker for air pollution from traffic, the more easily measured variables degree of urbanization, traffic density, and distance to a nearby highway can all be used to estimate exposure to traffic-related air pollution. Key words: distance, exposure, highways, nitrogen dioxide, traffic, urbanization. — Environ Health Perspect 109(suppl 3):411–417 (2001). http://ehpnet1.niehs.nih.gov/docs/2001/suppl-3/411-417rijnders/abstract.html

During the last decade, air pollution in relation to respiratory health has again become an important issue. In addition to indoor sources, automobile traffic has been recognized as a major source of air pollution exposure. Traffic emissions consist of volatile hydrocarbons, airborne particles, nitrogen oxides, and carbon monoxide. Several recent studies suggest an association between air pollution from traffic and adverse effects on respiratory health (1–6). In many of these studies, crude measures of exposure to traffic-related air pollution, such as traffic density on the street of residence and/or distance of the home address to busy roads, are used (1,2). Some other studies have used air pollution levels measured at a central ambient site or in the schools of the children (3–5). Few studies have incorporated personal measurements of traffic-related air pollution, either as a direct measure of exposure or as a validation of the exposure measures used (6,7).

Several studies show that ambient air pollution from traffic is higher in urban areas than in rural or nonurban areas (8–10). For example, in the PEACE study, a multicenter study of acute pollution effects on asthmatic children in Europe, the median urban/rural ratio pooled over all 14 locations was 1.8 for nitrogen dioxide (NO₂) and 1.4 for black smoke (8). Although none of these studies have related air pollution concentrations to some measure of the actual degree of urbanization, it can be expected that with increasing degree of urbanization, for example, expressed as the number of addresses per unit area, exposure to traffic-related air pollution will increase as well.

Studies have shown also that air pollution from traffic is higher along busy roads compared to background locations (11–13). Air pollution from traffic in city districts near highways is related to the traffic density of the highway, distance of the measuring site to the highway, and the percentage of time that the measuring site was downwind of the highway (14). The range in concentrations between the city districts located along highways with different traffic densities was larger than the variation with distance from the highway within city districts. It was therefore suggested that exposure to traffic-related air pollution varies less among subjects living within the same city district than among subjects living along highways with different traffic densities. This study was designed to test two (null) hypotheses: a) there is no difference in exposure to NO₂ as a marker of traffic-related air pollution among subjects living in areas with a different degree of urbanization; and b) there is no difference in exposure to NO₂ as a marker of traffic-related air pollution among subjects living close to highways with different traffic intensities.

Materials and Methods

We used NO₂ as a marker for traffic-related air pollution (3,6). Personal exposure to NO₂ was measured in children from six different schools. Three schools were situated in city districts with varying degrees of urbanization, with no busy streets within 300 m of the schools. The other three schools were within 400 m of highways with varying traffic densities. In addition to personal measurements of the children, parents were asked to perform outdoor NO₂ measurements at the back side of their homes. Weekly averaged measurements were conducted during four different seasons.

Study Locations

For the first part, three schools were chosen located in areas with various degrees of urbanization. The degree of urbanization, developed by the Dutch Central Bureau of Statistics, is based on the average address density per unit area. It classifies all Dutch municipalities in 5 degrees of urbanization, with 1 being the most-populated level and 5 the least-populated level, so that each group has approximately the same number of inhabitants. Three schools from municipalities with a degree of urbanization of 1 (very urban), 3 (fairly urban), and 5 (nonurban) were selected from all schools in the center of the Netherlands (Utrecht province). Schools were selected on the basis of two criteria: a) the degree of urbanization of the postal code area of the school was the same as for the whole municipality; and b) the schools were more than 300 m from busy roads. The urban densities of the postal code areas of the selected schools were 3,792; 1,481; and 195 addresses per square kilometer for degree of urbanization of 1, 3, and 5, respectively. The years of construction of the school buildings were 1937, 1985, and 1967 for degree of urbanization of 1, 3, and 5, respectively.

For the second part of the study, 3 schools were chosen from 24 schools participating in
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a study on health effects of exposure to traffic-related air pollution of children attending six schools simultaneously. For logistic reasons it was not possible to conduct all measurements in the same week in the summer. Therefore, the measurements of the urbanization schools and traffic schools were conducted in 2 separate weeks. The school along the highway with the highest traffic density did not participate during the summer season.

Sampling sites of indoor measurements at school were located in the classrooms of the participating children, away from windows and doors. Outdoor measurements at the schools were conducted at the back side of the school at approximately 1.5-2 m above the ground. Children received verbal instructions from one of the investigators at the school on how to take care of their samplers. Passive sampling tubes were attached to a badge and worn between breast and head. Outdoor samples were given to the children, with written instructions for the parents. With the aid of photographs and examples, these written instructions explained the use of the personal exposure badges of their children and the measurement of outdoor NO2 at their homes. Personal exposure sampling was started and stopped at school. In small groups of five, children were asked to uncap tubes and after 1 week, to recap their tubes under supervision. The supervising researcher registered date and time. Parents were instructed to attach the outdoor tubes to the back side of their homes using a specially designed device and to write down on a form the time of uncapping and recapping. The sampled outdoor tubes were hand in by the children on the same day that the personal exposure samples were collected. Tubes handed in after the collection day were sent back by mail by the teacher, using a preaddressed envelope. Collected tubes handed in after the collection were sealed and stored in a refrigerator until analysis (within 3 months). To motivate children, teachers were given a present.

Exposure Variables

Information on potential indoor sources of NO2 in the homes of the children and other characteristics was assessed using a self-administered questionnaire distributed at the beginning of the project.

For children from the three schools near a highway, the distance of the home from the highway, defined as the distance between the center of the postal code area of the home address to the highway, was calculated using a geographic information system (GIS). In addition, wind direction was used to evaluate the percentage of time the schools were downwind of the highway during the measurement periods. Data on wind direction per hour were obtained from Rotterdam Airport Zestienhoven of the Royal Dutch Meteorological Institute. The percentage of time that a school had been downwind of the highway was calculated by determining a 120° sector surrounding the perpendicular line connecting the school to the highway (14).

Data Analysis

First, the distribution of personal and outdoor NO2 concentrations was calculated for each school and season separately. Differences among the schools were tested using a t-test. Because of the known strong
influence of unvented gas water heaters on indoor NO2 concentrations in the Netherlands (17,18), children whose parents reported that they had such a water heater were excluded from the analysis.

Combined analysis of data from all four seasons was performed using a multiple regression model in which three dummy variables for each season were included. The SAS procedure “Proc Mixed” (SAS Institute, Cary, North Carolina, USA) was used to adjust regression results for correlations between repeated measurements of the same child. A random intercept model was used. The all-seasons combined effect of degree of urbanization or traffic density on personal and outdoor NO2 was calculated using both the categoric urbanization/traffic density levels (very, fairly, non) as the continuous urbanization/traffic density variables (addresses per square kilometer and vehicles per 24 hr for urbanization and traffic density, respectively).

For both groups of three schools, combined season analyses for personal exposure were also calculated after adjusting for the following potential indoor sources of NO2: unvented gas water heater, vented gas water heater, gas cooker, parental smoking, and a gas space heater in the living room. For the traffic density schools the distance between the home address and the highway was added to the model. We expected an exponential decay of the concentrations with increasing distance from the road (14), so we used the logarithm of the distance. Furthermore, we evaluated any significant differences in the personal/outdoor ratios between the schools that, if present, could point to differences in personal exposures between the schools caused by factors other than the outdoor NO2 concentrations or the indoor sources mentioned previously.

Results

Population

Characteristics of the participating children are shown in Table 2. The number of participants was smallest for the schools in the area with the highest degree of urbanization and along the busiest highway. Potential indoor sources were generally present more in the homes of the children from the highest exposure category, especially for the urbanization schools. In total, 14 children lived in a home with an unvented gas water heater (“geiser”). In most households, gas was used for cooking.

NO2 Concentrations and Degree of Urbanization

Results of the classroom and outdoor NO2 measurements at the schools in areas with varying degrees of urbanization are presented in Table 3. Except for the classroom concentrations in autumn, classroom concentrations and outdoor concentrations at the back side of the schools were in all seasons highest in the area with the highest degree of urbanization and lowest in the area with the lowest degree of urbanization. The difference among average classroom concentrations in the very urban and nonurban school (12.2 µg/m³) was somewhat larger than the difference among the average outdoor concentrations (11.4 µg/m³). This indicates that the indoor/outdoor ratio (I/O) was larger for the very urban school (yearly average I/O = 0.6) compared to the other two urbanization schools (yearly average I/O = 0.4). As there are no important indoor sources of NO2 in these classrooms, this is possibly the result of higher ventilation of the very urban school in the very urban area. This is supported by the fact that this school building was much older (pre-World War II) than the other two school buildings.

The distributions of personal and home outdoor NO2 concentrations in areas with varying degrees of urbanization are presented in Table 4. In all seasons, both personal and outdoor NO2 concentrations were highest in the area with the highest degree of urbanization and lowest in the area with the lowest degree of urbanization. The difference between outdoor concentrations in the very urban and nonurban areas was significant in all seasons except autumn, which may be due to the low number of outdoor concentrations in the very urban area (n = 9). When comparing the very urban with the fairly urban area, we found significant differences (p < 0.05) in autumn, winter, and spring for personal exposures, and in winter, spring, and summer for outdoor concentrations.

When the data from all seasons were combined, the estimated difference between the area with the highest degree of urbanization and the area with the lowest degree of urbanization was 14.6 µg/m³ (standard error of the mean [SE] 1.7) for personal exposures.

Table 2. Characteristics of the participating children.

| Characteristic          | Urbanization schools | Traffic schools |
|-------------------------|----------------------|-----------------|
|                         | Very urban (n = 33)  | Fairly urban (n = 56) | Nonurban (n = 43) | Very busy (n = 27) | Fairly busy (n = 39) | Nonbusy (n = 44) |
|                         | n/addresses/km²    | n/addresses/km² | n/addresses/km² | n/addresses/km² | n/addresses/km² | n/addresses/km² |
| Girls                   | 19/58               | 32/57           | 24/56           | 12/48           | 20/51           | 22/50           |
| Unvented gas water heater | 5/15            | 0/56            | 0/56            | 5/20            | 2/5             | 2/5             |
| Vented gas water heater | 8/24               | 1/24            | 2/5             | 3/12            | 0/5             | 6/14            |
| Cooking with gas        | 33/100              | 48/66           | 29/67           | 24/100          | 31/82           | 34/79           |
| Parental smoking        | 22/82               | 24/43           | 22/51           | 17/68           | 14/38           | 28/64           |
| Gas space heater in living room | 3/9           | 5/9             | 15/35           | 2/8             | 3/8             | 8/18            |
| Dutch origin            | 10/33               | 52/93           | 43/100          | 21/94           | 33/95           | 36/82           |
| Low-education mother    | 15/58               | 3/6             | 2/5             | 8/36            | 2/5             | 8/18            |
| Low-education father    | 16/57               | 3/6             | 5/13            | 2/10            | 1/3             | 6/14            |
| Home within 400 m of the highway | 16/64       | 20/51           | 32/74           | 21/64           | 32/62           | 43/100          |
| Home within 1,000 m of the highway |             |                 |                 |                 |                 |                 |

*Primary school only.

Table 3. Mean classroom and outdoor NO2 concentrations at schools in areas with varying degrees of urbanization.

| Period (dd/mm/yy) | Very urban (n = 33) | Fairly urban (n = 56) | Nonurban (n = 43) | Very busy (n = 27) | Fairly busy (n = 39) | Nonbusy (n = 44) |
|-------------------|---------------------|-----------------------|-------------------|-------------------|---------------------|-----------------|
| n/addresses/km²   | n/addresses/km²     | n/addresses/km²       | n/addresses/km²   | n/addresses/km²   | n/addresses/km²     | n/addresses/km² |
| Autumn (24/11/97–01/12/98) | 20.9 | 8.0 | 9.3 | 31.6 | 27.6 | 26.7 |
| Winter (10/02/98–17/02/98) | 29.6 | 16.0 | 12.4 | 59.0 | 41.6 | 33.2 |
| Spring (17/04/98–24/04/98) | 22.9 | 13.4 | 12.3 | 32.4 | 29.2 | 26.8 |
| Summer (19/06/98–26/06/98) | 19.0 | 12.4 | 9.6  | 24.8 | 20.5 | 15.7 |
| Average            | 23.1               | 12.5                 | 10.9             | 37.0             | 29.7             | 25.6             |

*Mean of 2–4 classrooms.
and 11.0 µg/m³ (SE 0.9) for outdoor concentrations. The estimated differences between the area with the intermediate degree of urbanization and the area with the lowest degree of urbanization were 3.9 µg/m³ (SE 1.3) for personal exposures and 5.0 µg/m³ (SE 0.6) for outdoor concentrations. Table 4 shows that for the school in the very urban area the range in personal NO₂ concentrations was large in both winter and summer, which in both seasons is caused by an outlying high concentration from the same child (who lived in a home with a vented gas water heater). Removing these outliers somewhat decreased the estimated difference in personal exposures between the very urban and nonurban area (from 14.6 to 12.3 µg/m³). When the degree of urbanization of the home address in addresses per square kilometer instead of the categoric urbanization level of the school was included in the model, an increase in NO₂ concentrations of 3.4 µg/m³ per 1,000 addresses per km² was estimated for both personal and outdoor concentrations (SE 0.4 and 0.3, respectively).

**NO₂ Concentrations and Traffic Density**

Table 5 shows the percentages downwind, classroom concentrations, and outdoor concentrations during the measurement periods. On average, the percentage of time that the school was downwind of the highway during the measurements was 15% higher for the school with the lowest traffic density compared to the other two schools. Outdoor NO₂ concentrations at the back side of the schools were, on average, highest for the school along the very busy highway and lowest for the school along the nonbusy highway. Mean classroom concentrations were for all seasons highest in the school along the very busy highway but did not differ much between the two other schools.

The distributions of the personal and home outdoor NO₂ concentrations for children living near highways are presented in Table 6. In all seasons, personal and outdoor NO₂ concentrations were significantly higher for the very busy highway compared to the nonbusy highway. NO₂ concentrations along the fairly busy highway were significantly higher compared to the nonbusy highway in the winter and spring season. For outdoor NO₂ this was also the case in the summer season. Significant differences in personal and outdoor NO₂ concentrations between the very busy and fairly busy highway were found only in the autumn period.

Combining the seasons for 1 year resulted in an estimated difference of 8.2 µg/m³ (SE 1.8) between personal NO₂ exposure of the children from the school with the highest traffic density and the school with the lowest traffic density. Personal NO₂ exposure of the children from the school with the intermediate traffic density was 2.6 µg/m³ (SE 1.4) higher compared to the school with the lowest traffic density. For outdoor NO₂ concentrations these differences were 9.6 µg/m³ (SE 1.1) and 4.9 (SE 0.8), respectively. When total traffic density of the highway as a continuous variable was included in the model, an increase in NO₂ concentrations of 2.6 µg/m³ (SE 0.6) per 50,000 vehicles per 24 hr was estimated for personal exposure and 3.5 µg/m³ (SE 0.4) per 50,000 vehicles per 24 hr for outdoor concentrations. Adding the logarithm of the distance of the home address to the highway to the model did not strongly influence the estimates for traffic density (both categoric and continuous). Outdoor concentrations significantly decreased with increasing distance. The estimated decrease was −1.3 µg/m³ per log(m) (SE 0.4). This corresponds to a difference of 1.8 µg/m³ when comparing the concentration at 100–m distance to the concentration at 400-m...
distance. For personal NO₂ concentrations the influence of distance of the home address was smaller (−0.9 µg/m³ per log(m); SE 0.8) and not significant.

### Indoor Sources

As expected, having an unvented gas water heater in the home strongly influenced personal NO₂ exposures, with an estimated contribution of 27.0 µg/m³ (SE 4.4) for the urbanization schools and 19.8 µg/m³ (SE 2.7) for the traffic schools. A vented gas water heater had a smaller but also significant influence on personal NO₂ exposures of 5.4 µg/m³ (SE 3.1) and 8.9 µg/m³ (SE 2.5) for the urbanization and traffic schools, respectively. Cooking with gas also significantly contributed to personal NO₂ exposures, with an estimated contribution of 2.4 µg/m³ (SE 0.9) for the urbanization schools and 2.3 µg/m³ (SE 1.3) for the traffic schools. Parental smoking or having a gas space heater in the living room did not significantly influence personal NO₂ exposures.

Differences in personal NO₂ exposures between the urbanization and traffic categories remained significant after adjusting for potential indoor sources. For the urbanization schools, the estimated difference between the very urban and nonurban school, after excluding data from children with either an unvented or vented gas water heater and after adjusting for cooking with gas, parental smoking, and a gas space heater in the living room, was 10.1 µg/m³ (SE 1.2). This is lower than the uncorrected value of 14.6 µg/m³, suggesting that the unadjusted difference was partly caused by indoor sources. The adjusted difference between the fairly urban and nonurban school was 3.3 µg/m³ (SE 0.8), which is similar to the unadjusted value of 3.9 µg/m³. For the traffic schools, the difference between the very busy and nonbusy highway did not change (8.2 µg/m³; SE 1.6) and the difference between the fairly busy and nonbusy highway increased from 2.6 µg/m³ to 4.5 µg/m³ (SE 1.1). Furthermore, the adjusted model showed a significant decrease in personal NO₂ exposure with increasing distance of the home address from the highway of −1.4 µg/m³ per log(m) (SE 0.6), whereas in the uncorrected analysis this decrease was smaller and not significant. Including some socioeconomic factors, such as Dutch origin, parental education, or the age of the home, did not change the results.

When all data included in Table 4 were used, the average personal/outdoor ratio was about 0.2 (p < 0.01) higher for the very urban school compared to the other two urbanization schools, again pointing toward a stronger influence of indoor sources on personal NO₂ exposures of children from the very urban school. After excluding data from children with (un)vented gas water heaters in their homes, and after adjusting for cooking with gas, parental smoking, and the presence of a gas space heater in the living room, the difference was less than 0.1 and no longer statistically significant. No significant differences between the personal/outdoor ratios between the traffic schools were found in any of the analyses.

### Comparison between Urbanization and Traffic Density Schools

Because measurements were conducted in all six schools simultaneously in autumn, winter, and spring, a direct comparison between schools from the two different parts of the study is possible for these three seasons. Outdoor concentrations at the back side of the schools (Tables 3, 5) were generally higher for the schools along highways compared to the other school with the same degree of urbanization (very busy and fairly busy compared to very urban and not busy compared to fairly urban). Classroom concentrations were, on average, higher in the school along the busiest highway compared to the very urban school and in the school along the least busy highway compared to the fairly urban school. Classroom concentrations, however, were considerably lower in the fairly busy compared to the very urban school.

Home outdoor concentrations were significantly higher along highways. The combined season estimated differences were 6.7 µg/m³ and 3.0 µg/m³ for the very busy and fairly busy highway compared to the very urban school, and 2.5 µg/m³ for the nonbushy highway compared to the fairly urban school. Personal exposures, however, were not higher along highways. Personal exposures were actually significantly lower along the fairly busy highway than in the very urban area (estimated difference 5 µg/m³; SE 2).

### Discussion

This study has shown that personal and outdoor NO₂ concentrations were significantly different among children living in areas with different degrees of urbanization and among children living in areas close to highways with different traffic densities.

Several other studies have documented significantly higher NO₂ concentrations in urban areas compared to nonurban, suburban, or rural areas (19–22). The estimated differences between the very urban and nonurban area of 10 and 11 µg/m³ for personal and outdoor concentrations, respectively, correlate well with the differences found in other European studies with similar NO₂ levels (19–22). In a study in Helsinki, Finland, personal NO₂ exposures of 246 children 3–6 years of age from eight day-care centers in downtown and suburban areas measured during 13 weeks were about 9 µg/m³ higher in the downtown area (geometric mean, 26.5 µg/m³) than in the suburban area (geometric mean, 17.5 µg/m³) (19). Krämer et al. (6) measured outdoor and personal NO₂ exposures as part of a study on the health effects of traffic pollution on children living in two urban and one suburban area. Estimated annual personal and outdoor NO₂ concentrations were 5–7 µg/m³ and 12–17 µg/m³ higher, respectively, in the urban areas compared to the suburban area.

Less information is available about NO₂ concentrations in city districts along highways with varying traffic densities. The 3 schools that participated in this study were selected out of 24 schools that participated in a study on health effects of exposure to traffic-related air pollution of children attending schools near highways (15). In that study, indoor and outdoor NO₂ concentrations measured at the schools were significantly correlated with total traffic density of the highway. The estimated contribution of total traffic was 3 µg/m³ per 50,000 vehicles for both outdoor and indoor air, which is similar to the values found in this study (2.6 and 3.5 µg/m³ per 50,000 vehicles for personal and home outdoor concentrations, respectively). In a previous study on air pollution near highways in the Netherlands, we also found a significant correlation (r = 0.68) between total traffic density and indoor NO₂ concentrations in 12 schools (14). In that study, mean classroom NO₂ concentrations varied between 9.2 µg/m³ at 393 m of a highway with a total traffic density of 81,000 vehicles per 24 hr to 32.8 µg/m³ at 33 m from a highway with 135,000 vehicles per 24 hr.

Krämer et al. (16) found a correlation (r = 0.70) between outdoor NO₂ and an index characterizing the amount of traffic in front of the child’s home. Personal NO₂ exposures were only marginally correlated with outdoor NO₂ (r = 0.37).

Personal and home outdoor NO₂ concentrations significantly decreased with increasing distance of the home address to the highway. The estimated decrease was 1.3 and 1.4 µg/m³ per log(m) for home outdoor and personal NO₂, respectively, corresponding to a decrease of about 2 µg/m³ when expressed as the difference between 100 and 400 m distance. Compared to the difference observed between the very busy freeway and the quiet freeway, which was more than 10 µg/m³, this difference was modest, indicating that traffic density on a freeway is a more important determinant of personal NO₂ exposure than distance of home or school from the freeway.

For all 24 schools a somewhat higher but nonsignificant value of 1.9 µg/m³ per log(m) was found for both outdoor and classroom concentrations (15). In our previous study on air pollution near highways, we also found a
significant correlation between indoor NO$_2$ concentrations in classrooms and distance of the school to the highway ($r = -0.83$). Furthermore, outdoor NO$_2$ measurements at various distances from the same highway showed a clear gradient ($r = 0.4$). Two other studies in open terrain downwind of a highway also found a decline in NO$_2$ concentrations with distance (23,24). Nakai et al. (7) measured personal, indoor, and outdoor NO$_2$ concentrations in three zones at different distances from two busy roads in Tokyo, Japan. Mean outdoor concentrations decreased from 81 µg/m$^3$ in zone A (< 20 m) to 67 µg/m$^3$ in zone B (20–150 m) and 39 µg/m$^3$ in the reference zone (zone C). Average personal NO$_2$ exposures in the non-heating season were 60, 56, and 32 µg/m$^3$ for zone A, B, and C, respectively. Two other Japanese studies also documented associations between NO$_2$ concentrations and distance to major roads (20,25).

Differences between the schools remained significant after excluding children with either vented or unvented gas water heaters in their homes (the two known strongest indoor sources of NO$_2$ in the Netherlands) and after adjusting for cooking with gas, parental smoking, and a gas space heater in the living room. Including some socioeconomic variables or housing characteristics also did not change the results. In view of our specific research hypothesis, other unidentified indoor sources can only invalidate our conclusions in case the presence of these factors is associated with the degree of urbanization or traffic density. Randomly distributed indoor sources could only have obscured the observed relationship between personal NO$_2$ and traffic. It is unlikely that any unidentified indoor source is sufficiently strong and sufficiently overrepresented in the highest exposure category to explain the observed differences between the schools. The same holds for other factors that may influence personal NO$_2$ exposures, such as activity patterns. Furthermore, after adjusting for indoor sources, personal/outdoor ratios did not significantly differ between the schools, which further supports the conclusion that the differences in personal exposures between the schools are most likely caused by differences in outdoor concentrations and not by indoor sources or housing characteristics.

The schools along the very and fairly busy highway were situated in an area with a lower degree of urbanization, at similar distances from the road, and with the same geographic orientation toward the road, these differences are most likely caused by the difference in traffic densities of the highways. The difference between these two schools and the school along the highway with the lowest traffic density could (partly) have been caused by a difference in urbanization. Conversely, the latter school was situated closer to the road and was about 15% more downwind of the highway than the first two schools during the measurements. This could have resulted in a smaller difference between the fairly busy and nonbusy highway than would have been observed if all schools had been situated at the same distances from the road and had been downwind for a similar percentage of time. Personal NO$_2$ exposures were significantly higher for children who lived in homes with a gas-fired water heater, especially when the water heater had no ventilation duct. This is in line with previous Dutch NO$_2$ monitoring studies, which have shown that these kinds of water heaters are a major source of indoor NO$_2$ in the Netherlands (17,18). For example, Fischer et al. (18) found an estimated difference in personal NO$_2$ between women living in homes with and without a gas water heater of 24 µg/m$^3$ in the case of an unvented water heater and 12 µg/m$^3$ in the case of a vented gas water heater. Cooking with gas also significantly increased personal NO$_2$ concentrations, but this influence was small (± 2 µg/m$^3$) compared to the influence of an unvented gas water heater. This is in line with several other studies that have documented significant higher personal NO$_2$ concentrations for children (19,26) or adults (22) living in homes where gas is used for cooking. Parental smoking did not significantly influence personal NO$_2$ exposures. Most of the studies mentioned previously have found higher personal or indoor NO$_2$ concentrations for smokers or children exposed to environmental tobacco smoke (19–22,26). The estimated differences, however, are generally small and not always present in all subgroups. For example, in the study among preschool children in Helsinki, personal NO$_2$ exposures were, on average, about 4 µg/m$^3$ higher for children living with smokers in the suburban area (electric cooking only). In the urban area, however, personal NO$_2$ exposures were higher (± 3 µg/m$^3$) only for children living with smokers in homes where gas was used for cooking, whereas no difference was found for children living in homes with electric cooking (19).

**Conclusion**

This study has shown that personal and outdoor NO$_2$ concentrations are significantly influenced by the degree of urbanization of the city district and by the traffic density of and distance to a nearby highway. As NO$_2$ can be considered a marker for air pollution from traffic, a) degree of urbanization, b) traffic density, and c) distance to a nearby highway can all be used to estimate exposure to traffic-related air pollution.

**REFERENCES AND NOTES**

1. Weiland SK, Mundt KA, Rockman A, Keil U. Self-reported wheezing and allergic rhinitis in children and traffic density on street of residence. Ann Epidemiol 4:234–242 (1994).
2. Ciceo G, Forastiere F, Agabiti N, Birgin A, Bisanti L, Chellini E, Corbo G, Dell’Oro V, Dalmaso P. Road traffic and adverse respiratory effects in children. Occup Environ Med 55:771–778 (1998).
3. Studnicka M, Hackl E, Fischinger J, Fangmeyer C, Haschke N, Köhr J, Urbäniak R, Neumann M, Frischer T. Traffic-related NO$_2$ and the prevalence of asthma and respiratory symptoms in seven-year olds. Eur Respir J 10:2775–2789 (1997).
4. Brunekreef B, Janssen NAH, de Hartog J, Harssema H, Knape M, van Vliet P. Air pollution from truck traffic and lung function in children living near motorways. Epidemiology 12:298–303 (2001).
5. van Vliet P, Knape M, de Hartog J, Janssen N, Harssema H, Brunekreef B. Motor vehicle exhaust and chronic respiratory symptoms in children living near freeways. Environ Res 74:122–132 (1997).
6. Köhner U, Koch T, Ranft U, Ring J, Behrendt H. Traffic-related air pollution is associated with asthma in children living in urban areas. Epidemiology 11:64–70 (2000).
7. Nakata S, Kitta H, Maeda K. Respiratory health associated with exposure to automobile exhaust. J. Personal NO$_2$ exposure levels according to distance from the roadside. J Expo Anal Environ Epidemiol 5:125–136 (1995).
8. Lee DS, Garland JA, Fox AA. Atmospheric concentrations of trace elements in urban areas of the United Kingdom. Atmos Environ 28:2691–2713 (1994).
9. Smith DJT, Harrison RM. Concentrations, trends and vehicle source profile of polycyclic aromatic hydrocarbons in the UK atmosphere. Atmos Environ 30:2513–2525 (1996).
10. Hoek G, Forsberg B, Borowikows M, Wiałkowiak S, Vaskövi E, Welinder H, Brans M, Benee I, Kotesovec F, Hagen LO, et al. Wintertime PM10 and black smoke concentrations across Europe: results from the PEACE study. Atmos Environ 39:6205–6222 (2005).
11. Janssen NAH, van Mansom DFM, van der Jagt J, Harssema H, Hoek G. Mass concentration and elemental composition of airborne particulate matter at street and background locations. Atmos Environ 31:1185–1193 (1997).
12. Kirby C, Greig A, Drye T. Temporal and spatial variations in
nitrogen dioxide concentrations across an urban landscape: Cambridge, U.K. Environ Monit Assess 52:65–82 (1998).

13. Fischer PH, Hoek G, Reesvijk H, Briggs DJ, Lebret E, van Wijnen JH, Kingham S, Elliot PE. Traffic related differences in outdoor and indoor concentrations of particles and volatile organic compounds in Amsterdam. Atmos Environ 34:3713–3722 (2000).

14. Roorda-Knape M, Janssen NAH, de Hartog J, van Vliet P, Hanssena H, Brunekeef B. Air pollution from traffic in city districts near major highways. Atmos Environ 23:1921–1930 (1998).

15. Janssen NAH, van Vliet PHN, Aarts F, Hanssena H, Brunekeef B. Assessment of exposure to traffic related air pollution of children attending schools near motorways. Atmos Environ (in press).

16. Palmes ED, Gunnison AF, DMartin T, Tomczyk C. Personal sampler for nitrogen dioxide. Am Ind Hyg Assoc J 37:570–577 (1976).

17. Remijn B, Fischer P, Brunekeef B, Lebret E, Boelej JS, Noij O. Indoor air pollution and its effect on pulmonary function of adult non-smoking women. I: Exposure estimates for nitrogen dioxide and passive smoking. Int J Epidemiol 14:215–220 (1985).

18. Fischer P, Brunekeef B, Boelej JS, JSM. Indoor NO₂ pollution and personal exposure to NO₂ in two areas with different outdoor NO₂ pollution. Environ Monitor Assess 8:221–229 (1986).

19. Alm S, Mukanla K, Pasanen P, Tiititanen P, Ruuskanen J, Tumisto J, Juntuinen M. Personal pollution of preschool children in Helsinki. J Expo Anal Epidemiol 8:79–100 (1998).

20. Shima M, Adachi M. Indoor nitrogen dioxide in homes along trunk roads with heavy traffic. Occup Environ Med 55:428–433 (1998).

21. Raaschou-Nielsen O, Skov H, Lohse C, Thomsen BL, Olsen JH. Front-door concentrations and personal exposures of Danish children to nitrogen dioxide. Environ Health Perspect 105:964–970 (1997).

22. Moen C, Brandli O, Schindler C, Ackermann-Liebrich U, Leuenberger P. Personal exposure to nitrogen dioxide in Switzerland. SAPALDIA team. Sci Total Environ 215:243–251 (1998).

23. Rodes CE, Holland DM. Variations of NO, NO₂, and O₃ concentrations downwind of a Los Angeles freeway. Atmos Environ 15:243–250 (1981).

24. Kahler M, Kraft J, Koch W, Wind H. Dispersion of car emissions in the vicinity of a highway. In: Environmental Meteorology. Dordrecht, Netherlands:Kluwer Academic Publishers, 1998;39–47.

25. Nitta H, Sata T, Nakano S, Maeda K, Aoki S, Dano M. Respiratory health associated with exposure to automobile exhaust. I: Results of cross-sectional studies in 1979, 1982 and 1983. Arch Environ Health 48:53–58 (1993).

26. Linaker CH, Chauhan AJ, Inskip H, Free A, Sillence A, Coggon D, Holgate ST. Distribution and determinants of personal exposure to nitrogen dioxide in school children. Occup Environ Med 53:200–203 (1996).