

## ORIGINAL ARTICLE

## Respiratory health and individual estimated exposure to traffic-related air pollutants in a cohort of young children

V Morgenstern, A Zutavern, J Cyrus, I Brockow, U Gehring, S Koletzko, C P Bauer, D Reinhardt, H-Erich Wichmann, J Heinrich

*Occup Environ Med* 2007;**64**:8–16. doi: 10.1136/oem.2006.028241

**Objectives:** To estimate long-term exposure to traffic-related air pollutants on an individual basis and to assess adverse health effects using a combination of air pollution measurement data, data from geographical information systems (GIS) and questionnaire data.

**Methods:** 40 measurement sites in the city of Munich, Germany were selected at which to collect particulate matter with a 50% cut-off aerodynamic diameter of 2.5 µm (PM<sub>2.5</sub>) and to measure PM<sub>2.5</sub> absorbance and nitrogen dioxide (NO<sub>2</sub>). A pool of GIS variables (information about street length, household and population density and land use) was collected for the Munich metropolitan area and was used in multiple linear regression models to predict traffic-related air pollutants. These models were also applied to the birth addresses of two birth cohorts (German Infant Nutritional Intervention Study (GINI) and Influence of Life-style factors on the development of the Immune System and Allergies in East and West Germany (LISA)) in the Munich metropolitan area. Associations between air pollution concentrations at birth address and 1-year and 2-year incidences of respiratory symptoms were analysed.

**Results:** The following means for the estimated exposures to PM<sub>2.5</sub>, PM<sub>2.5</sub> absorbance and NO<sub>2</sub> were obtained: 12.8 µg/m<sup>3</sup>, 1.7 × 10<sup>-5</sup> m<sup>-1</sup> and 35.3 µg/m<sup>3</sup>, respectively. Adjusted odds ratios (ORs) for wheezing, cough without infection, dry cough at night, bronchial asthma, bronchitis and respiratory infections indicated positive associations with traffic-related air pollutants. After controlling for individual confounders, significant associations were found between the pollutant PM<sub>2.5</sub> and sneezing, runny/stuffed nose during the first year of life (OR 1.16, 95% confidence interval 1.01 to 1.34). Similar effects were observed for the second year of life. These findings are similar to those from our previous analysis that were restricted to a subcohort in Munich city. The extended study also showed significant effects for sneezing, running/stuffed nose. Additionally, significant associations were found between NO<sub>2</sub> and dry cough at night (or bronchitis) during the first year of life. The variable "living close to major roads" (<50 m), which was not analysed for the previous inner city cohort with birth addresses in the city of Munich, turned out to increase the risk of wheezing and asthmatic/spastic/obstructive bronchitis.

**Conclusions:** Effects on asthma and hay fever are subject to confirmation at older ages, when these outcomes can be more validly assessed.

See end of article for authors' affiliations

Correspondence to:  
Dr J Heinrich, GSF, National Research Center for Environment and Health, Institute of Epidemiology, Ingolstaedter Landstrasse 1, D-85764 Neuherberg, Germany; joachim.heinrich@gsf.de

Accepted 4 August 2006  
Published Online First  
15 August 2006

Only a few studies, mainly in Europe, have investigated the effects of traffic-related air pollution on human health. There is an ongoing debate about long-term exposure to traffic-related air pollutants, as chronic effects on respiratory health<sup>1–3</sup> and even mortality have been documented in several studies.<sup>4–5</sup> With respect to health effects, the most common investigated traffic-related air pollutant is particulate matter.

As a major source of particulate matter, traffic substantially contributes to the overall effect of outdoor air pollution.<sup>6</sup> Although epidemiological research is needed, exposure assessment issues for traffic-related air pollutants are complex and need to be considered before undertaking investigations of health effects. As vehicle emissions, by definition, take place on roads, people who live close to major roads might be expected to be exposed to higher concentrations of traffic-related air pollutants and have a higher risk of adverse health effects. Several studies have shown higher rates of respiratory illness and symptoms and reduced lung functions in people living close to busy roads.<sup>1–13</sup> Several studies showed that exposure to nitrogen dioxide (NO<sub>2</sub>)<sup>14–15</sup> and particulate matter,<sup>16</sup> as well as proximity to motorways,<sup>17</sup> are associated with respiratory health symptoms.

A powerful tool to estimate individual exposure to traffic-related air pollutants is geographical information systems

(GIS)-based modelling. GIS provides the means to capture, store, process and display spatial data. In contrast with self-reported traffic intensities, GIS models have a lot of advantages.<sup>18–19</sup> Assessments of exposure to traffic-related air pollutants based on questionnaire reports, for example, can lead to serious misclassifications. Thus, individuals may overestimate the traffic intensity in their neighbourhood as high, even if the traffic load in the whole community is low.

GIS-based models can also include information from larger areas by taking different buffer zones into account. Up to now, only a few studies have combined geographical data with concentration measurements to calculate individual exposure.<sup>2–20–22</sup>

In the framework of the European Union-funded Traffic-Related Air Pollution and Childhood Asthma (TRAPCA) project, regression models were developed and applied to the residential addresses of 1756 children who lived in the city of Munich, Germany.<sup>2</sup> We extended our existing model<sup>23</sup> to the Munich

**Abbreviations:** ATKIS, Authoritative Topographic-Cartographic Information System; GINI, German Infant Nutritional Intervention Study; GIS, geographical information system; LISA, Influence of Life-style factors on the development of the Immune System and Allergies in East and West Germany; RMSE, root mean squared error; TRAPCA, Traffic-Related Air Pollution and Childhood Asthma

metropolitan area, which includes the city of Munich and surrounding districts. Using the extended study population of this area, we tested the hypothesis whether increased exposure to traffic-related air pollutants in children is associated with a higher risk of developing inhalant allergy, asthma or other chronic respiratory conditions than in children with low exposure.

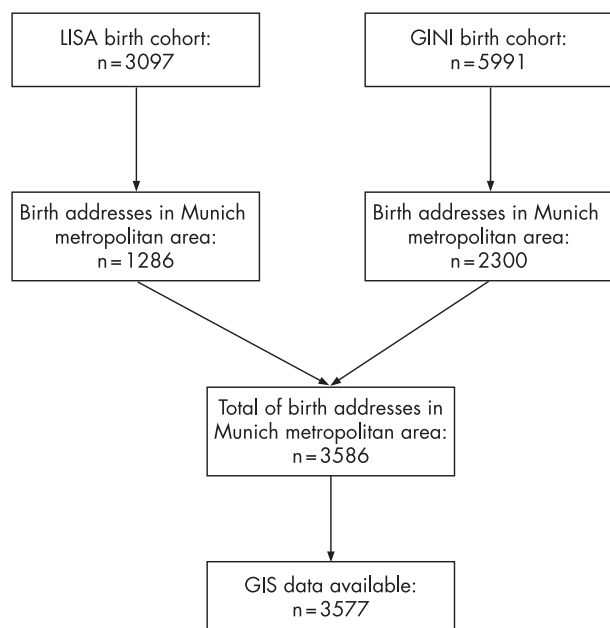
For this study, we developed GIS-based regression models for particulate matter with a 50% cut-off aerodynamic diameter of  $2.5 \mu\text{m}$  ( $\text{PM}_{2.5}$ ),  $\text{PM}_{2.5}$  absorbance and  $\text{NO}_2$  for the Munich metropolitan area and applied these models to the residential addresses of the members of two birth cohorts. Further, we analysed the association between exposure to traffic-related air pollutants, living close to major roads and health effects at 2 years of life.

## MATERIAL AND METHODS

### Study population and study area

With our data, we estimated the exposure to traffic-related air pollutants of the children from two prospective birth cohort studies (German Infant Nutritional Intervention Study (GINI) and Influence of Life-style factors on the development of the Immune System and Allergies in East and West Germany (LISA)) in the Munich metropolitan area. Detailed descriptions of the designs of these cohort studies have been published elsewhere.<sup>24–25</sup>

Briefly, the GINI birth cohort consists of 5991 healthy newborns, who were recruited in Munich and Wesel (fig 1). A subgroup of 2300 children lived in the Munich metropolitan area. The LISA birth cohort consists of 3097 children from Munich, Leipzig, Wesel and Bad Honnef, of whom 1286 children lived in the Munich metropolitan area. The TRAPCA II Munich birth cohorts included 3586 children from the GINI and LISA studies residing in the Munich metropolitan area. No GIS data were available for 11 children. Thus, the final birth cohort consisted of 3577 children. Compared with the former TRAPCA I study cohort ( $n = 1756$ ),<sup>2,3</sup> the extension of the study area doubled the number of children in the study population.



**Figure 1** The German Infant Nutritional Intervention Study (GINI) and Influence of Life-style factors on the development of the Immune System and Allergies in East and West Germany (LISA) birth cohorts in the Munich metropolitan area.

The original TRAPCA study was conducted in the city of Munich, the capital of Bavaria, in the south of Germany. In December 2005, Munich had a population of about 1.29 million inhabitants<sup>26</sup> covering an area of  $310 \text{ km}^2$ . After including the surrounding suburbs (rural Munich, Ebersberg, Fürstenfeldbruck, Starnberg, Freising, Erding and Dachau), the area covered about  $1200 \text{ km}^2$ .

### Location of measurement site

In total, 40 measurement sites in the city of Munich were selected. In accordance with the TRAPCA protocol and to better assess the exposure of our related birth cohort, which is located in particular in the southern half of Munich, the majority ( $n = 25$ ) of sites were located there. All sites were divided into traffic ( $n = 17$ ) and background sites ( $n = 23$ ). Both background and traffic sites were defined as sites that had no obvious sources of combustion or particulate matter (industry, construction, heating plants, etc) within a 50-m radius. In addition, background sites were not located within 50 m of busy streets carrying  $>3000$  vehicles/day, whereas traffic sites were typically located near busy streets.<sup>27</sup> The median sampler height was 2 m (range 2–15 m). Additional details regarding TRAPCA site characterisation have been published elsewhere.<sup>27–28</sup>

### Air pollution measurements

All particulate matter and  $\text{NO}_2$  measurements were made during 2-week intervals between March 1999 and July 2000. Sampling periods were approximately 14 days, during which air was sampled for 15 min every 2 h for a total of approximately 42 hours per sampling period. Four measurements were taken at each of the 40 sites, so that each site was measured once in each season.

Particles were collected on Anderson Teflon membrane filters (37 mm diameter, pore size  $2 \mu\text{m}$ ) using Harvard Impactors (Air Diagnostics & Engineering, Naples, Maine, USA) to collect  $\text{PM}_{2.5}$  as described elsewhere.<sup>27</sup> The air was sampled for 15 min every 2 h for a total of approximately 42 hours per sampling period. Pump flow rates were set to 10 l/min, and sampling flows were measured before and after each sampling period. The collection time was recorded by an electronic timer. For more details, see Brauer *et al.*<sup>2</sup>

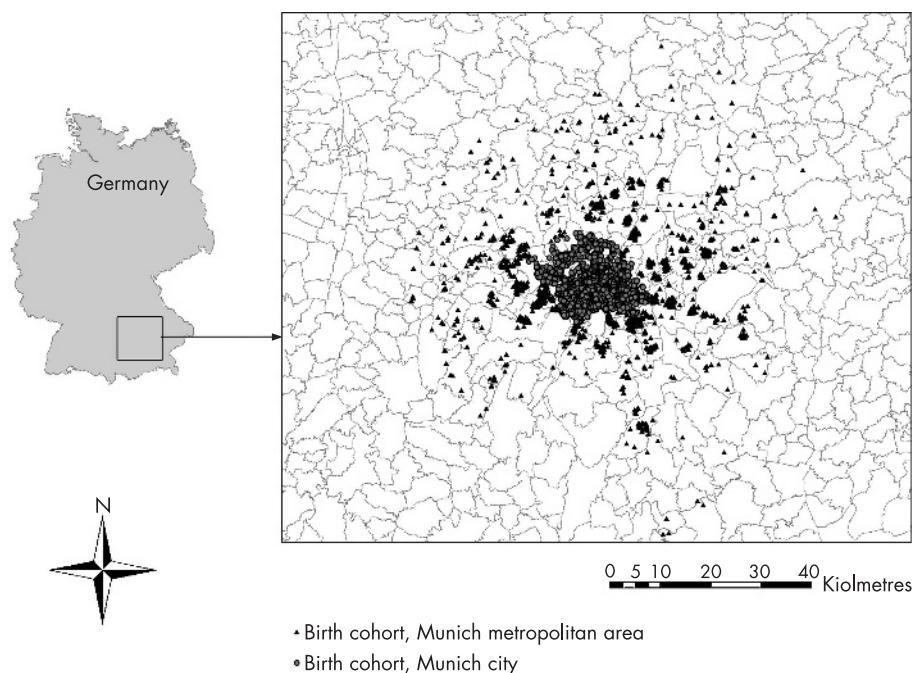
Reflectance measurements were made by the Institute for Risk Assessment Sciences Laboratory in The Netherlands with a Smoke Stain Reflectometer (Model 43, Diffusion Systems Hanwell, London, UK).  $\text{NO}_2$  concentrations were measured by Palmes tubes and the tubes were analysed for nitrite by ion chromatography as described elsewhere.<sup>29</sup>

### Geographical information

Annual average air pollution concentrations were calculated and related to GIS variables. For the GIS variables, we applied buffers of different radii. All geographical variables were collected and stored using Arc GIS 9.1 (ESRI, Redlands, California, USA).

Four major sets of GIS variables were defined: distances to streets, length of street segments, population and household density, and land use. These variables are obtained as follows.

For the road network, we used a shapefile of the object-type street (3101) from the Authoritative Topographic-Cartographic Information System (ATKIS)-digital landscape models from the Bavarian Surveying Office in Munich. The ATKIS is a common project of the survey administrations of the Federal Republic of Germany. The ATKIS provided a digital database of the landscape and terrain relief. Objects of the “real” world, such as roads, rivers or woodlands, have been stored in digital landscape models. This shapefile, however, does not contain



**Figure 2** Geographical location of the birth cohorts.

traffic intensities, but categorises the roads with the following levels: motorways (Autobahn), federal roads (Bundesstrasse), state roads (Staatsstrasse), county roads (Kreisstrasse) and rural roads (Gemeindestrassen). This categorisation of the streets refers to the official street categorisation in Germany. Motorways are designed to carry a large volume of traffic without any general speed limit. They are usually dual-carriageway roads with two or more lanes in each direction. Federal roads, however, are long-distance roads through several German states, but with a general speed limit of 100 km/h. State roads carry the traffic more or less within the different states of Germany, and thus are less frequented than federal roads. County roads are mainly built for the traffic between cities and villages in the different districts. Rural roads are built and maintained by the communities, and are thus quite small roads, mainly in villages or little towns.

Thus, total street lengths in each buffer zone could be computed by summation. Distances were calculated taking the shortest possible distance from the measurement site to the street.

For traffic data, circular buffers with radii of 50, 100, 250, 500, 1000, 2500 and 5000 m were created around the coordinates of interest and intersected with the road network. Thus, the length of the street segments could be added up.

We obtained demographic information (the numbers of inhabitants and households in every postcode area in Bavaria) from the company Infas GEOdaten (Bonn, Germany). These data were actualised in December 2003. As data about population and household densities are only given for each postcode area, the proportions of the postcode area, the proportions of the population and household counts, respectively, were calculated for each buffer. Therefore, the buffers need to be intersected with the postcode areas. Area-weighted averages of the population and household numbers in every buffer were calculated, and are referred to as population and household densities.

Information about land use was obtained as a 100-m grid from CORINE (Co-ordination of Information on the

Environment, Copenhagen, Denmark) Land Cover. This database describes vegetation and land use in 44 classes, with a minimum mapping element of 25 ha. Thus, it yields fine spatial resolution of existing vegetation over a large part of Europe.<sup>30 31</sup> Images acquired by earth observation satellites are used to derive information on land cover.

Characteristics of the measurement sites and addresses were derived from the raw geographical data by calculating total counts for certain neighbourhoods. We computed a land cover factor for the different buffers similar to the SAVIAH study.<sup>20 32</sup> Additionally, we obtained information about the following land use classes: artificial surfaces, agricultural areas, forests and seminatural areas, wetlands and water bodies.

The Gauss–Krüger coordinate system was used as the spatial reference for the geographical features. The coordinates of the measurement sites and the cohort addresses have been geocoded by the Bavarian Surveying Office, Munich.

### Exposure assessment

As it was not feasible to measure personal exposure to the traffic-related air pollutants  $\text{NO}_2$ ,  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  absorbance for all study subjects, exposure modelling was used. As the measurements at the 40 sites were taken in different periods, a temporal component caused by the changing background concentration had to be eliminated from the measurements, which has been done by a difference method.

We analysed the relationship between the independent GIS variables and the annual average air pollution concentrations for the 40 measuring sites by multiple linear regression models. The regression-based exposure modelling offers particular potential in this field, involving least squares regression techniques to generate predictive models for the pollutants based on measured data and exogenous information.<sup>20</sup>

Data on the relevant input variables were calculated for a series of buffers (50–5000 m) around each measuring site.

Firstly, we calculated separate models for the four main sets of independent variables including the different buffer sizes.

Then, we selected the most relevant spatial scales by separately entering all the buffer sizes and then determining the percentage of the explained variation. The buffer with the highest adjusted  $R^2$  was selected. Next, we built up a regression model including the most influential variables using the most relevant buffer scales from all sets of variables. Finally, we carefully checked whether these models could be improved by entering further geographical variables.

### Questionnaire data

All data on health outcomes and potential confounding variables were obtained through questionnaires that were completed by the parents. Members of the LISA cohort received a questionnaire at birth and then every 6 months, whereas parents of the GINI cohort answered a questionnaire annually.

### Statistical analysis

The correlation of continuous variables is assessed by the Pearson correlation coefficient ( $r$ ). The fit of linear regression models is given by the percentage of variation explained ( $R^2$ ).

We used the cross-validation procedure to assess the precision of the exposure models based on the measurements from the 40 sites and the GIS variables. The prediction error was expressed as root mean squared error (RMSE), calculated as the square root of the sum of the squared differences of the observed concentration at site  $i$  and the predicted concentration at site  $i$  from the model developed without site  $i$ .

We tested the association between exposure and health outcomes by multiple logistic regression, with adjustment for potential confounding factors. Individual confounders were

used, which had been identified in our previous study,<sup>3</sup> such as sex, parental atopy, maternal education, siblings, environmental tobacco smoke at home, use of gas for cooking, home dampness, indoor moulds and keeping pets. Furthermore, we looked at the association between living close to major roads and the health effects. The cut-off for the variable "living close to major road" was 50 m. This was based on the hypothesis that the largest contribution from large streets to air pollution is expected at short distances.

All odds ratios (ORs) are presented against interquartile range increases in air pollution concentrations. Significance was defined by a two-sided  $\alpha$ -level of 5%, and thus, 95% confidence intervals (CIs) were obtained. All statistical analyses were carried out using SAS V.8.02.

## RESULTS

### Study population

The prediction models were applied to all 3577 children. Data on respiratory health effects for 3129 children were available at the age of 1 year. Table 1 summarises the lifetime prevalences. There are no major differences in prevalence rates between the cohorts from the Munich metropolitan area and Munich city. Figure 2 shows the geographical location of the extended TRAPCA II cohort in the Munich metropolitan area. The TRAPCA I cohort, which has been restricted to the city of Munich, is also shown.

### Geographical data

Table 2 shows the mean and range of the continuous predictor variables for the measurement sites ( $n=40$ ) and the birth cohorts ( $n=3577$ ). We regard the lengths of street segments as

**Table 1** Description of the study cohort

Variable	Munich metropolitan area (including Munich city)		Munich city	
	Prevalence n/N	%	Prevalence n/N	%
<b>Symptoms and diseases</b>				
At the age of 1 year*				
Wheezing	471/3037	15.5	258/1722	15.0
Cough without infection	261/2908	9.0	151/1655	9.1
Dry cough at night	207/3056	6.8	123/1737	7.1
Doctor-diagnosed bronchial asthma	12/3055	0.4	6/1731	0.4
Doctor-diagnosed asthmatic/spastic/obstructive bronchitis	356/3059	11.6	196/1735	11.3
Doctor-diagnosed respiratory infections	2168/3052	71.0	1212/1728	70.1
Sneezing, running/stuffed nose without a cold	406/3067	13.2	254/1743	14.6
At the age of 2 years*				
Wheezing	746/2882	25.9	416/1627	25.6
Dry cough at night	387/2866	13.5	228/1614	14.1
Doctor-diagnosed bronchial asthma	26/2833	0.9	16/1600	1.0
Doctor-diagnosed asthmatic/spastic/obstructive bronchitis	555/2861	19.4	303/1616	18.8
Doctor-diagnosed respiratory infections	2733/3021	90.5	1528/1695	90.2
Sneezing, running/stuffed nose without a cold	610/2907	21.0	354/1638	21.6
<b>Confounding variables</b>				
Female sex	1489/3129	52.4	832/1756	47.4
Parental atopy	1667/3577	46.6	935/1756	53.3
ETS at home	646/3008	21.5	398/1704	23.4
Maternal education				
<12 grades	925/3113	29.7	633/1751	36.1
≥12 grades	1853/3113	59.5	1118/1751	63.9
Siblings	1358/3080	44.1	700/1712	40.9
Use of gas for cooking	253/3075	8.2	221/1731	12.8
Home dampness	218/3080	7.1	115/1731	6.6
Indoor moulds	934/3082	30.3	534/1735	30.8
Keeping pets	658/3100	21.2	318/1739	18.3
Cat	304/3092	9.8	159/1735	9.2
Dog	160/3092	5.2	70/1735	4.0

ETS, environmental tobacco smoke.

\*Lifetime prevalences.

**Table 2** Continuous predictor variables for the measurement sites (n=40) and the birth cohort (n=3577)

Variable	Measurement sites		Birth cohort	
	Mean (m)	Range (m)	Mean (m)	Range (m)
Distance to nearest federal road	1896.42	314.81–3376.76	1575.92	14.29–12138.89
Distance to closest motorway	128.10	0–275.60	2046.59	56.46–24893.45
Length of rural roads (100–250 m)	2045.23	441.24–3927.06	2031.24	1537.27–4036.83
Length of rural roads (250–500 m)	6792.21	3765.17–10926.62	6313.34	4680.79–11748.14
Length of rural roads (2500–5000 m)	551997.18	733786.91–2055943.42	531476.13	693386.93–1945395.42
Length of county roads (0–1000 m)	0	0–653.14	0	0–4498.83
Length of motorway (2500–5000 m)	56.98	14.65–141.36	271.21	0–2658.97
Length of state roads (1000–2500 m)	2430.17	0–11861.50	5872.78	0–11748.14
Household density (2500–5000 m)	72633	19481–125443	31644	435–132100
Population density (500–1000 m)	4486	1790–18091	2496	96–17044

indicators for traffic load. Thus, the traffic load was, on average, lower at the addresses of the birth cohorts than at the measurement sites. By contrast, the traffic generated on rural roads is similar for the measurement sites and the residential addresses of the GINI and LISA children living in the Munich metropolitan area.

The household and population densities were much higher at our measurement locations than at the addresses of the study population. Correlations between the different predictor variables in general could be decreased by using ring buffers (eg, household density in the buffer between 25 and 100 m).

As for the TRAPCA I model, the population and household densities were highly correlated at all spatial scales ( $r > 0.8$ ). The street length of the different streets and the population densities for the same buffers, however, were moderately correlated ( $-0.25 < r < 0.5$ ).

### Exposure models

Table 3 presents the final GIS models used for the calculation of the cohort exposures. For calculating the exposure models, only those variables that were available for the measurement sites and for the cohort addresses were used.

For  $PM_{2.5}$  and  $PM_{2.5}$  absorbance, we found the best models with only four explanatory variables, whereas for the other model, more predictors were needed to reach the best fit. Further extensions of the models would have led to more implausible coefficients and even to smaller values for the adjusted  $R^2$ .

In all three models, the land coverage factor is a powerful predictor. The same result was obtained for the household or rather population density, which is included in all models with a big buffer (2500–5000 m).

In our previous analysis restricted to Munich city,<sup>2,3</sup> we obtained nearly the same model fit for the  $NO_2$  prediction model ( $R^2 = 0.51$  v  $0.62$  in the previous analysis); for  $PM_{2.5}$  mass and absorbance, both previous models explained more variation than the models developed here ( $R^2 = 0.56$  v  $0.36$ , and  $0.67$  v  $0.47$ , respectively).

To obtain information about the validity of our models, we used the cross-validation method. The square root of the RMSE is  $0.46 \times 10^{-5}/m$  for  $PM_{2.5}$  absorbance,  $1.48 \mu g/m^3$  for  $PM_{2.5}$  and  $9.51 \mu g/m^3$  for  $NO_2$ . For the TRAPCA I model, the values for  $PM_{2.5}$  and  $NO_2$  were approximately 50% lower. The RMSE was lower at background sites for  $PM_{2.5}$  and  $PM_{2.5}$  absorbance than for traffic sites, but not for  $NO_2$ .

### Application of exposure models to birth addresses

The exposure models described earlier were then applied to the birth home addresses of the children to assess traffic-related air pollution concentrations at the children's homes. All addresses of the children had to be geocoded, and for all children the same GIS data that were used in the regression models had to be collected.

Table 4 gives the distribution of the estimated exposures to the traffic-related air pollutants for the Munich metropolitan area with the extended model.

**Table 3** Results of regression models for particulate matter with a 50% cut-off aerodynamic diameter of  $2.5 \mu m$  ( $PM_{2.5}$ ),  $PM_{2.5}$  absorbance and nitrogen dioxide

Variable	Slope	Standard error	Sequential $R^2$
Model for $PM_{2.5}$			
Land coverage factor (100–250 m)	2.56570	0.896	0.358
Length of rural roads (100–250 m)	$0.847 \times 10^{-3}$	$0.364 \times 10^{-3}$	0.167
Distance to nearest motorway	$-0.22740 \times 10^{-3}$	$0.273 \times 10^{-3}$	0.144
Population density (500–1000 m)	$0.10374 \times 10^{-3}$	$0.752 \times 10^{-4}$	0.013
Model for $PM_{2.5}$ absorbance			
Household density (2500–5000 m)	$4.58 \times 10^{-5}$	$2.68 \times 10^{-6}$	0.420
Distance to nearest federal roads	$-1.322 \times 10^{-4}$	$5.855 \times 10^{-5}$	0.249
Land coverage factor (100–250 m)	0.464	0.223	0.069
Length of county roads (0–1000 m)	$5.500 \times 10^{-4}$	$4.984 \times 10^{-4}$	0.060
Model for $NO_2$			
Length of state roads (1000–2500 m)	$6.171 \times 10^{-4}$	$5.661 \times 10^{-4}$	0.510
Land coverage factor (100–250 m)	8.821	3.772	0.327
Land coverage class	-3.447	2.444	0.084
Household density (2500–5000 m)	$5.997 \times 10^{-5}$	$4.152 \times 10^{-5}$	0.059
Length of rural roads (250–500 m)	$5.457 \times 10^{-4}$	$7.671 \times 10^{-4}$	0.032
			0.008

$NO_2$ , nitrogen dioxide;  $PM_{2.5}$ , particulate matter with a 50% cut-off aerodynamic diameter of  $2.5 \mu m$ .

**Table 4** Annual average concentrations for particulate matter with a 50% cut-off aerodynamic diameter of 2.5 µm (PM<sub>2.5</sub>), PM<sub>2.5</sub> absorbance and nitrogen dioxide estimated for the residential addresses

	Percentile							
	Min	10th	25th	50th	Mean	75th	90th	Max
PM <sub>2.5</sub> (µg/m <sup>3</sup> )	6.8	11.9	12.5	12.9	12.8	13.3	13.6	15.3
PM <sub>2.5</sub> absorbance (10 <sup>-5</sup> m <sup>-1</sup> )	1.3	1.6	1.6	1.7	1.7	1.8	2.0	3.2
NO <sub>2</sub> (mg/m <sup>3</sup> )	19.4	30.1	32.5	35.4	35.3	38.2	39.6	71.7

Max, maximum; Min, minimum; NO<sub>2</sub>, nitrogen dioxide; PM<sub>2.5</sub>, particulate matter with a 50% cut-off aerodynamic diameter of 2.5 µm.

The spatial variation in the exposure to traffic-related air pollutants assessed with the TRAPCA I and the TRAPCA II models is similar; the closer the children live to the city centre, the more they are exposed to air pollutants. The means of the estimated air pollutants are similar for PM<sub>2.5</sub> absorbance. For NO<sub>2</sub> and PM<sub>2.5</sub>, we recorded higher values with the extended model. For NO<sub>2</sub>, the correlation between the estimates from the old and new models was weak ( $r = 0.29$ ); the correlations for PM<sub>2.5</sub> and PM<sub>2.5</sub> absorbance were moderate ( $r = 0.51$  and  $0.56$ ).

With the estimates from the new model, exposures to PM<sub>2.5</sub>, PM<sub>2.5</sub> absorbance and NO<sub>2</sub> for the Munich metropolitan area ranged from 6.8 to 15.3 µg/m<sup>3</sup>, from 1.3 to 3.2 × 10<sup>-5</sup>/m and from 19.4 to 71.7 µg/m<sup>3</sup>, respectively.

For our study cohort, we found moderate correlations for the estimated levels of NO<sub>2</sub> and PM<sub>2.5</sub> absorbance ( $r = 0.59$ ). The levels for PM<sub>2.5</sub> and PM<sub>2.5</sub> absorbance and NO<sub>2</sub> and PM<sub>2.5</sub> are weakly correlated ( $r = 0.49$  and  $0.45$ ).

### Relationship between ambient exposure to air pollutants and symptoms

Table 5 gives the associations between exposure to air pollutants and respiratory symptoms. After controlling for individual confounders, significant associations were found for the first year between the pollutant PM<sub>2.5</sub> and sneezing, runny/stuffed nose (OR 1.16, 95% CI 1.01 to 1.34) and between PM<sub>2.5</sub> absorbance and sneezing, runny/stuffed nose (OR 1.30 95% CI 1.03 to 1.65). We observed similar effects for the second year of life. Additionally, for the association between NO<sub>2</sub> and dry cough at night, and NO<sub>2</sub> and bronchitis, we found significant effects for the first year of life.

Figure 3 shows that increased levels of NO<sub>2</sub> were associated with increased prevalence of respiratory health symptoms. Exposures estimated with the extended model (TRAPCA II) for Munich city had the widest CIs. In the second year of life, the effects became significant for the cohort of the children living in the Munich metropolitan area. We found positive associations between sneezing, runny/stuffed nose, wheezing and NO<sub>2</sub> for the first and second years of life for the suburbs of Munich, and thus for the Munich metropolitan area. For Munich city centre, these effects were lower.

## DISCUSSION

This study addresses two challenging topics: the individual-specific exposure modelling for traffic-related air pollutants for our birth addresses and analysis of the health effects associated with the modelled exposures to PM<sub>2.5</sub>, PM<sub>2.5</sub> absorbance and NO<sub>2</sub>. For the first task, we developed regression models for the Munich metropolitan area with a reduced pool of GIS variables. By including data about land use, we increased the R<sup>2</sup> of our models. However, their percentage of variation did not reach the R<sup>2</sup> obtained in our previous study.<sup>3</sup> Here, we did not use data on traffic counts, which might be the main reason that the recent models have a slightly lower fit.

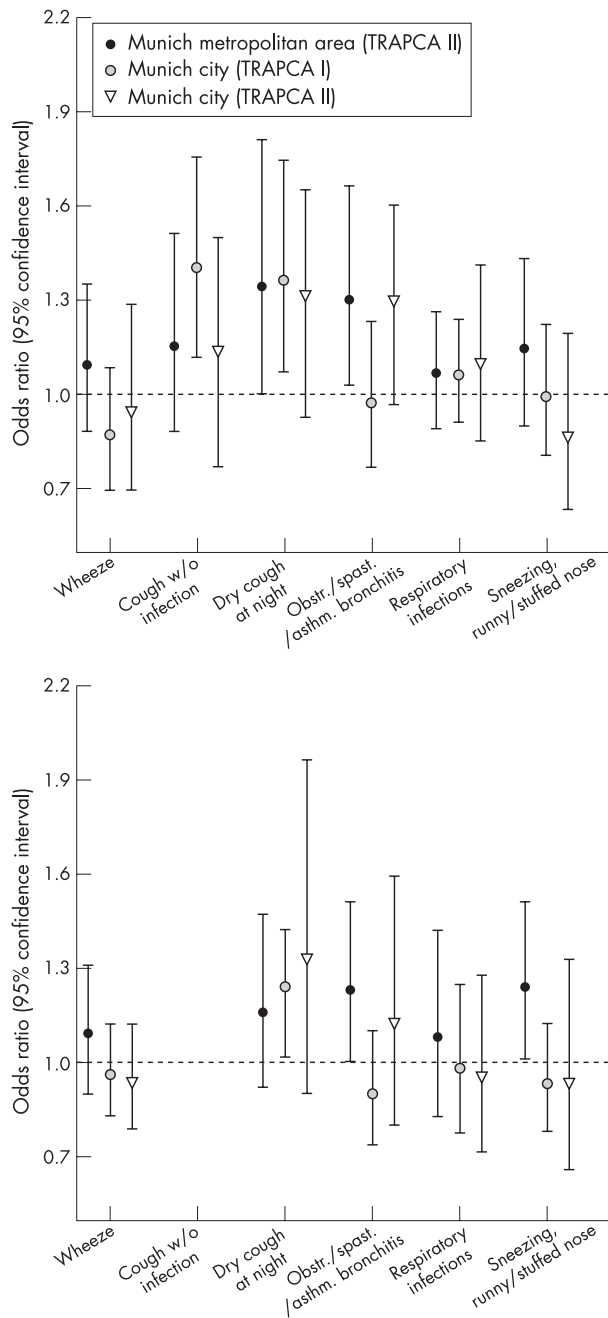
Similar to a study conducted in North-Rhine Westphalia, Germany,<sup>22</sup> we found that the combination of smaller and larger spatial scales forms the basis of good prediction models. As our study region comprises rural and urban areas, a large-scale predictor (2500–5000 m) is necessary, and variables in those buffers turned out to be predictive. In the previous TRAPCA study,<sup>23</sup> variables describing traffic intensity seemed to have greater explanatory power than those describing distance to nearby roads. For the extended model, we obtained information only about the street type as a proxy for traffic intensity, which means that our models could be improved when additional information becomes available. Population and household densities are a proxy for the general level of human activity in the vicinity of a monitoring site. They are associated with an increased traffic volume, and thus increased vehicle emissions. The household density on a large spatial scale turned out to be predictive for PM<sub>2.5</sub> absorbance and NO<sub>2</sub>.

The regression modelling technique has one major disadvantage: the development of significant but environmentally implausible exposure models. For this reason, we did not extend our models to more than four variables even if we could have increased the R<sup>2</sup>, to avoid the inclusion of counterintuitive variables, and we did not include variables with coefficients that are not in a meaningful direction.

Our GIS-based models assessed traffic-related air pollutants such as PM<sub>2.5</sub> mass, PM<sub>2.5</sub> absorbance and NO<sub>2</sub>. However, there are other sources of emissions besides traffic, including carbon monoxide or organic compounds, which are not covered by our regression models and which may not be highly correlated with the modelled pollutants. Another restriction is the extrapolation from outdoor pollution to personal exposure. In countries such as Germany, people tend to spend most of their time indoors. A US study reported that outdoor concentrations of NO<sub>2</sub> explained only 9–12% of variation in concentrations measured by personal monitors.<sup>33</sup> Thus, outdoor NO<sub>2</sub> is an indicator for traffic rather than for a toxic substance.<sup>4</sup>

The original TRAPCA study was designed for exposure assessment in the city of Munich. We, however, extended the existing model<sup>2</sup> to the suburbs of Munich, which might have limitations for the children living away from the city centre. Therefore, the models are more reliable for Munich city than for the surroundings of Munich. For the suburbs, we do not have any measurements, so far, with which we could validate our models. The estimated exposures from the extended model were only moderately correlated with the estimated exposures from the old model.<sup>2</sup> The different air pollutants estimated with the original TRAPCA model were highly correlated<sup>21</sup> ( $r > 0.95$ ), unlike those estimated with the extended model ( $r = 0.37$ – $0.59$ ). A reason for this, therefore, might be the fact that we used different predictor variables for the new model, which might cover the differences in the air pollutants better.

Despite these limitations, this new method of exposure assessment results in good predictions. This model can be compared with simpler approaches—for example, distance to



**Figure 3** Adjusted ORs and 95% CIs and respiratory symptoms associated with an interquartile range increase in nitrogen dioxide for the first year of life (top) and the second year of life (bottom). TRAPCA, Traffic-Related Air Pollution and Childhood Asthma.

nearest road<sup>14 17 34</sup> or self-reported traffic intensity.<sup>35–37</sup> As shown previously,<sup>18</sup> there are advantages to GIS-based modelling compared with modelling using self-reported traffic intensities. The strength of our study is that despite the GIS-based models, we also take into account the distances to major roads. This is a powerful method to assess associations between respiratory health symptoms and traffic, which operate at local scales. As our GIS-based models comprise mainly broad-scale predictors, we can better determine the local associations using distance to major roads.

In the second part of our study, we considered the associations between the modelled exposures to the traffic-related air pollutants and respiratory health effects. For that

### Policy implications

- Geographical information system-based regression models for traffic-related pollutant particulate matter with a 50% cut-off aerodynamic diameter of 2.5  $\mu\text{m}$  ( $\text{PM}_{2.5}$ ),  $\text{PM}_{2.5}$  absorbance and nitrogen dioxide were calculated and applied for 3577 children living in the Munich metropolitan area.
- For the first time in the Traffic-Related Air Pollution and Childhood Asthma study, the variable “living close to major roads”, which turned out to increase the risk of wheezing and asthmatic/spastic/obstructive bronchitis, was analysed.

reason, we used the same methods as presented in Gehring *et al*<sup>3</sup> and did not adjust for multiple testing. We found significant associations between  $\text{PM}_{2.5}$ ,  $\text{PM}_{2.5}$  absorbance and sneezing/runny/stuffed nose. Reports of dry cough at night and asthma were found to be associated with  $\text{NO}_2$  in the first year of life. For the second year of life, we could not confirm these findings. A reason could be that children in their first year of life are more sensitive towards respiratory health symptoms than those in the second year of life. Compared with our previous study,<sup>3</sup> the tendency of most of the effect estimates could be confirmed. However, different outcomes turned out to be significant. For the larger study population, dry cough at night is not significant. Gehring *et al*<sup>3</sup> stated that the reason for the positive association between air pollution and dry cough with regard to later development of inhalant allergies, asthma and chronic respiratory conditions was not clear. This needs to be investigated at older age group, when asthma and allergic rhinitis are better diagnosed. Furthermore, in our previous study,<sup>3</sup> stratified analyses for sex showed stronger effects in males compared with females. Using the cohort from the Munich metropolitan area, we could not confirm these findings. By contrast, we found stronger effects in females than in males, similar to the Dutch study.<sup>17</sup> Figure 3 clearly shows that by taking into account the bigger cohort for the Munich metropolitan area, some effects changed (eg, wheezing). The effect estimates for respiratory infections and dry cough at night, however, remained stable independent of the way of estimating the exposure to the pollutants. This could indicate that wheezing is more prevalent in the rural areas around our study region compared with the city centre (table 1).

In a Swiss study,<sup>38</sup> positive associations between exposure to outdoor  $\text{NO}_2$  and respiratory symptoms in children aged 0–5 years were shown. With regard to dry cough at night, the effects in our study were highest for  $\text{NO}_2$ . An increased duration of respiratory symptoms with increasing levels of  $\text{NO}_2$  was found in another study.<sup>39</sup>

As a marker for diesel exhaust particles, we measured  $\text{PM}_{2.5}$  absorbance. We were unable, however, to differentiate between heavy-duty and light-duty vehicles. Several studies have shown that trucks, typically fuelled with diesel in Germany, are associated with reduced lung functions and increased prevalence of chronic respiratory symptoms.<sup>7 17</sup> By calculating the ORs between the respiratory health symptoms and distances to major roads, this study is able to disentangle these effects.

Gordian *et al*<sup>11</sup> found that proximity to traffic at residence locations is associated with being diagnosed with asthma as a young child in Anchorage, Alaska, USA. As these children were aged 5–7 years, these findings are not exactly comparable, but suggest the GINI and LISA children should be looked at when they are older.

**Table 5** Association between long-term exposure to air pollution and lifetime prevalences of infections, asthmatic and allergic symptoms

Exposure variable	Adjusted* odds ratios of symptoms associated with interquartile range of air pollution variables (symptom variable)					
	Wheeze	Cough without infection	Dry cough at night	Asthmatic/spastic/obstructive bronchitis	Respiratory infections	Sneezing, runny/stuffed nose
<b>At the age of 1 year</b>						
	n=3037	n=2908	n=3056	n=3059	n=3052	n=3067
PM <sub>2.5</sub> (per 1.04 µg/m <sup>3</sup> )	1.01 (0.87 to 1.18)	1.05 (0.88 to 1.25)	1.08 (0.86 to 1.27)	1.04 (0.90 to 1.29)	1.05 (0.88 to 1.22)	1.16 (1.01 to 1.34)
PM <sub>2.5</sub> absorbance (per 0.22×10 <sup>-5</sup> /m)	0.97 (0.77 to 1.23)	1.16 (0.87 to 1.54)	1.09 (0.78 to 1.51)	1.14 (0.88 to 1.48)	1.03 (0.86 to 1.24)	1.30 (1.03 to 1.65)
NO <sub>2</sub> (per 5.7 µg/m <sup>3</sup> )	1.09 (0.88 to 1.35)	1.15 (0.88 to 1.51)	1.34 (1.00 to 1.81)	1.30 (1.03 to 1.66)	1.06 (0.89 to 1.26)	1.14 (0.90 to 1.43)
Distance to nearest main road <50 m (yes v no)	1.14 (0.92 to 1.42)	0.74 (0.55 to 1.00)	0.84 (0.61 to 1.16)	1.12 (0.88 to 1.44)	1.03 (0.86 to 1.23)	1.10 (0.87 to 1.39)
<b>At the age of 2 years</b>						
	n=2882		n=2866	n=2861	n=3021	n=2907
PM <sub>2.5</sub> (per 1.04 µg/m <sup>3</sup> )	1.10 (0.96 to 1.25)	NA	1.03 (0.89 to 1.19)	1.05 (0.92 to 1.20)	1.09 (0.94 to 1.27)	1.19 (1.04 to 1.36)
PM <sub>2.5</sub> absorbance (per 0.22×10 <sup>-5</sup> /m)	1.09 (0.90 to 1.33)	NA	1.18 (0.93 to 1.50)	0.85 (0.31 to 2.34)	1.05 (0.79 to 1.39)	1.27 (1.04 to 1.56)
NO <sub>2</sub> (per 5.7 µg/m <sup>3</sup> )	1.09 (0.90 to 1.31)	NA	1.16 (0.92 to 1.47)	0.82 (0.33 to 2.03)	1.08 (0.83 to 1.42)	1.09 (0.89 to 1.33)
Distance to nearest main road <50 m (yes v no)	1.06 (0.88 to 1.27)	NA	0.93 (0.73 to 1.18)	1.23 (1.00 to 1.51)	1.15 (0.87 to 1.53)	1.24 (1.01 to 1.51)

NA, not applicable; NO<sub>2</sub>, nitrogen dioxide; PM<sub>2.5</sub>, particulate matter with a 50% cut-off aerodynamic diameter of 2.5 µm.

\*Adjusted for sex, parental atopy, maternal education, siblings, environmental tobacco smoke at home, use of gas for cooking, home dampness, indoor moulds and keeping pets.

Van Vliet *et al*<sup>17</sup> showed that children living near major freeways in The Netherlands had an increased prevalence of respiratory symptoms. A higher association was reported for children living within a 100-m buffer around the freeways than for children living further away. These findings were confirmed by another Dutch study.<sup>7</sup>

In the field of environmental epidemiology, there are a lot of studies on this topic, but they used different tools either for exposure assessment or for determining the children's symptoms. Therefore, we believe that this study—with a combination of individual-based exposure assessment and questionnaire-derived information—adds to our knowledge of adverse health effects and traffic-related air pollutants.

## CONCLUSION

We developed regression models to estimate individual levels of long-term exposure to PM<sub>2.5</sub>, PM<sub>2.5</sub> absorbance and NO<sub>2</sub> for 3577 children in the Munich metropolitan area. Further, we found associations between exposure to the traffic-related air pollutants and symptoms of sneezing. An influence of living close to major roads (<50 m) on wheezing and asthmatic/spastic/obstructive bronchitis was found. As associations were based on outcome data collected in our birth cohorts at the age of 1 and 2 years, these findings are only initial indications and are subject to confirmation at older ages, when most outcomes can be more exactly diagnosed.

## Authors' affiliations

V Morgenstern, A Zutavern, J Cyrys, U Gehring, H-E Wichmann, J Heinrich, GSF National Research Center for Environment and Health, Institute of Epidemiology, Neuherberg, Germany  
 H-E Wichmann, Institute of Medical Data Management, Biometrics and Epidemiology, Ludwig-Maximilians University of Munich, Munich, Germany  
 A Zutavern, D Reinhardt, Kinderklinik und Kinderpoliklinik im Dr v Hauner'schen Kinderspital, Munich, Germany  
 J Cyrys, WZU, Environmental Science Center, University of Augsburg, Augsburg, Germany  
 I Brockow, S Koletzko, C P Bauer, Kinderklinik und Poliklinik der TU München, Munich, Germany; Institute for Risk Assessment Sciences, Utrecht University, Utrecht, The Netherlands

Competing interests: None declared.

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## ECHO.....

### Childhood cancers linked to roads and railways



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The development of cancer in children, particularly leukaemia, is strongly determined by prenatal or early postnatal exposure to engine exhaust gases, according to the findings of Knox, probably through maternal inhalation and accumulation of carcinogens over many months.

In a previous survey, the birth and death addresses of all children born in Great Britain between 1955 and 1980 who died from leukaemia or other cancers were linked to locations of railway stations, bus stations, ferry terminals, roads, canals, and rivers. The study had shown that many childhood cancers were initiated during fetal life or early infancy through exposure to atmospheric carcinogens, but the coarse resolution of available “emissions hotspots” maps created uncertainties.

Knox’s study attempted to overcome those limitations by extracting exact road, rail, and other data from the Ordnance Survey national digital archive and by re-examining the internal combustion engine (ICE) exhaust hypothesis on a fine geographical scale. Significant cancer birth places were found within short distances of bus and railway stations, ferries, railways, and A and B class roads and their surrounding commercial and industrial environments, with a relative risk of 2.1 within 100 metres tapering to neutral after 3 kilometres. About 24% of child cancers within 3 kilometres were attributed to these joint birth proximities. Roads exerted the major effect.

The main carcinogens are associated with engine exhausts, with the chief carcinogen likely to be 1,3-butadiene, probably inhaled and accumulated by the mother over a prolonged period.

This study raises urgent and important questions and monitoring of ICE exhaust emissions would seem to be prudent, especially with respect to 1,3-butadiene.

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